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FOR TRANSVERSELY FRAMED SHIPS

by

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STRUCTURAL ANALYSIS OF SIDE FRAMES OF TRANSVERSELY FRAMED SHIPS by RICHARD L. THOMAS. Submitted to the Department of Naval Architecture and Marine Engineering in partial fulfillment of the requirements for the Master of Science degree in Naval Architecture and Marine Engineering and the Professional degree of Naval Engineer.

ABSTRACT

The object of this work is to analyize the midship hold frames of transversely framed ships in an attempt to develop a rational design procedure for side frames. The analysis is concerned primarily with the hold frame as the most important member of the side frame.

A structural analysis for one member of a complex structure can be conducted by defining end fixations (boundary conditions) for the member which tend to duplicate those existing at the joint with contiguous structure. After determing values of relative stiffnesses for the transverse structural members of two cargo vessels, subsequent calculations indicated that reasonable end fixations for the top and bottom of the hold frame were 0.5 and 1.0 respectively.

The length of the hold frame was selected as the distance from the top of double bottoms to the lowest deck; this length, which includes the beam knee and the hold frame bracket, is felt to be structurally compatible with the selected end fixations. In order to provide some continuity in the calculations, all 'tween deck heights were assumed to be 8.5 ft; however, the number of 'tween deck heights was varied.

The axial load acting on the hold frame was determined to be one-half of all deck loads being carried over the distance of one frame space on a deck beam span from the hatch side girder to the side shell. The field moment due to the uniformly varying lateral load was defined, for the selected end fixations, by the application of simple beam theory. The ABS Rules approximate the uniformly varying load distribution by a uniform load distribution using the head of salt water acting at the midspan of the hold frame; the corresponding field moment was determined to permit an evaluation of this approximation.

The field moment and the axial load were calculated for a range of ship depths which were expressed in terms of ship length; in each case, Table 6 of the ABS Rules was utilized to determine the required hold frame scantlings.

Assuming 40t for the effective breadth of plating, the section modulus and section area were determined for increments of wastage allowance; using these section characteristics, the total stress, axial plus bending, was tabulated for the full load draft and for the full load draft increased by the crest of an L/20 wave height.

The credulity of the design analysis was strengthened when the required hold frame scantlings were associated with a total stress of 26,500 psi and a wastage allowance of 0.10 in. for the largest draft. Using the interaction formula, the resultant values of allowable axial stress approximated the requirements of various column design formulas. The uniform load approximation resulted in a total stress of 27,500 psi for the same wastage allowance.

The end fixations of 0.50 and 1.0 for the hold frame lead to a design procedure which is concluded to be rational and complete. The comparison of the design analysis with the requirements of the ABS Rules produced values of wastage allowance, total stress and allowable axial stress which are reasonable and consistent with good design practice.

Further research could be directed toward an analysis of the side frame and associated deck beams as a composite structure to compare the resultant end moments (implied end fixations) with those developed in this work.

Other secondary structural members should be submitted to an analysis similiar to that used in this work. Buckling of these members, including hold frames, is a subject which should be investigated.

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ACKNOWLEDGMENT

The author wishes to express his sincere appreciation to Professor J. Harvey Evans for his assistance and direction in motivating and preparing this analysis.

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I. INTRODUCTION

Naval architects and ship designers have made many contributions toward the ever increasing knowledge of engineering design principles. The results of these contributions are embodied within the extremely large ships constructed during the past decade, the developement of ship designs to perform new and different functions, and the increased understanding of structural behavior together with the developement of compatible methods of structural analysis. The latter is probably one of the most important contributions for it must be the basis for any successful, economic ship design.

The classification societies such as the American Bureau of Shipping define the minimum transverse strength requirements for secondary structural members* through the use of ship characteristics such as length, beam, and draft; the length of the member; and the use of numerals representing the loading on the member. One would assume that the Rule requirements were derived using the fundamentals of applied mechanics together with reasonable design assumptions and that any changes in the Rules were the result of service experience and a better understanding of structural behavior. The ABS, however, does not pro-

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* The term secondary structural members refers to side frames, web frames, deck beams, deck girders, bulkhead stiffeners, etc. which do not materially contribute to the longitudinal strength of the ship.

mulgate this information in terms of formulas or design procedures; therefore, the designer of a ship which is not within the range of Rule parameters must determine the scantlings of the structural members using his own experience with structural design procedures. To qualify for classification under the ABS, the resulting design would have to be reviewed, thereby causing undue delay during the design stage or perhaps even extensive re-design due to structural inadequacy.

It is the object of this thesis to analyize the mid-ship hold frames* of transversely framed ships in an attempt to develop a simple design procedure. The adequacy of the design procedure will be evaluated by its ability to reproduce the structural requirements of Section 8 and Table 6 of the Rules. (1)**

> The assumption is that such 'Rules' represent the most comprehensive body of data available which is reasonably representative of the lower limits of merchant ships' structural adequacy as demonstrated by service experience. (2)

The analysis and resulting design procedure is concerned primarily with the hold frame since it is the "key" member of a multi-deck side frame because:

1. It must withstand the largest lateral load due to

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* Hold frames are those frames located below the lowest tier of deck beams as opposed to 'tween deck frames which are designated type A, B, C or D in Figures II, III and IV.

** Numbers in parentheses refer to References in Appendix F.

Figure I

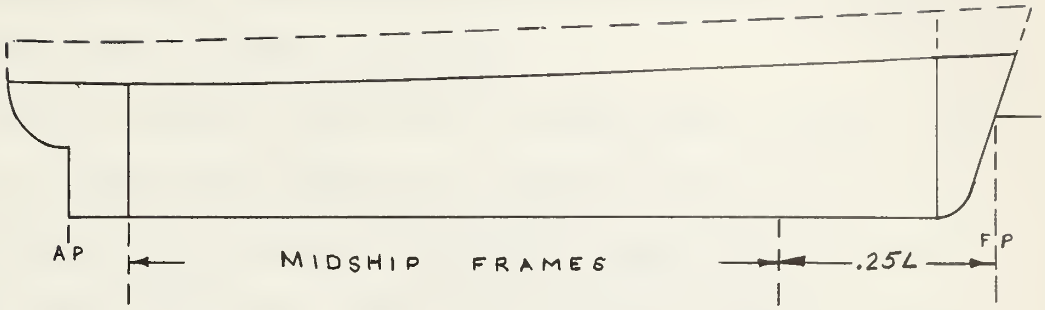


Figure II

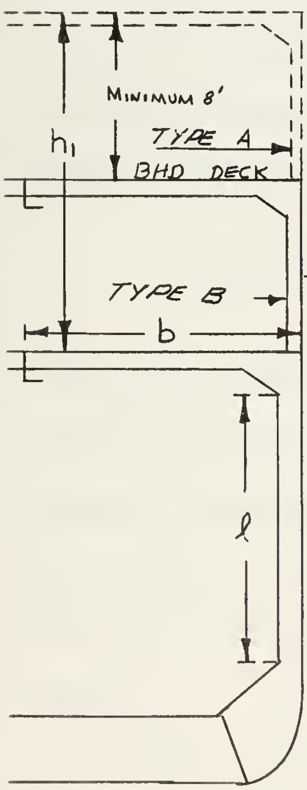


Figure III

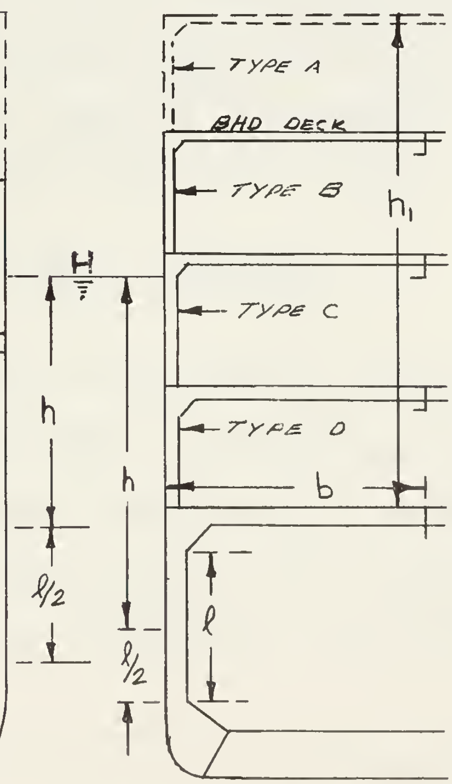
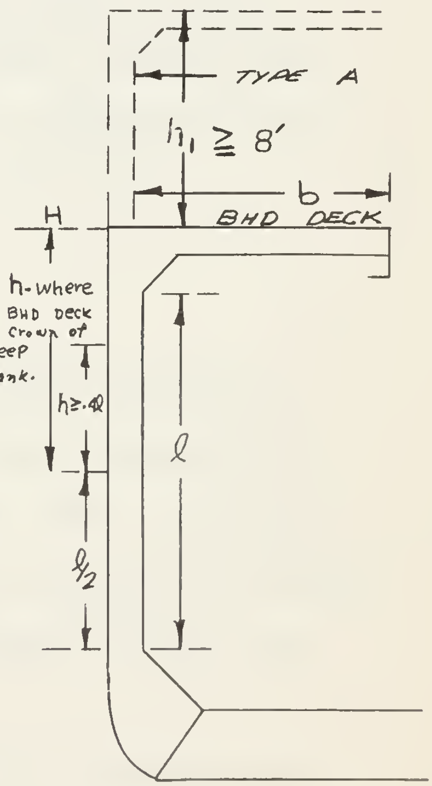


Figure IV



Reproduction of page 21, Section 8 of the ABS Rules Illustrating Nomenclature and Limitations.

external water pressure as well as an axial load due to all deck loads;

2. It functions as part of the connection acting to maintain transverse continuity between the side and double bottom structure.

In (3), Brown, states that in multi-deck ships, the size of 'tween deck frames are usually made smaller than hold frames in an attempt to realize some saving in hull weight; the resultant 'tween deck frames, however, should provide a reasonable degree of structural continuity with the hold frame.

Rule Requirements for Hold Frames

The scantlings of transverse hold frames are determined by entering Table 6 of the Rules with the unsupported span length, ℓ, as defined in Figures II, III and IV, together with a load numeral given by;

$$NF = \frac{s}{12}\left[h + \frac{h_{\prime} b}{(2)(50)}\right] \qquad (1)$$

The span length as illustrated in the above mentioned figures is applicable to ships with welded construction having beam knees fitted on each frame. The load numeral represents a combination of the lateral and axial loadings acting on the hold frame over the distance of one frame space.

The lateral load per foot of span is represented by the water pressure head, h, acting at the midlength of

the span or 0.4ℓ, whichever is greater. The axial load is represented by one-half of the deck loads being carried over a span length, b, on all decks above the hold frame. The Rules assume that a standard cargo density of 50 cu. ft. per long ton (3) or 44.8 lb. per cu. ft. is being carried to a height, h_1. The height, h_1, is defined as;

> The vertical distance in feet from the deck at the top of the frame to the Bulkhead or Freeboard Deck plus the height of all cargo 'tween deck spaces and one-half the height of all passenger spaces above the Bulkhead or Freeboard Deck or plus 8 feet if that be greater.(1)

A dimensional analysis of the load numeral reveals that the two factors have different units; specifically, the factors have the respective units of the loading they represent. The product $(sh)\rho \sim \frac{lb.}{ft.}$ defines a lateral loading per foot of span while $s\left(\frac{h_1 b}{50}\right) = 44.8\,(sh_1 b) \sim$ lb. defines an axial load.

NOMENCLATURE

Symbol			Units
A	=	cross-sectional area of frame section and effective breadth of plating	sq. in.
A_f	=	cross-sectional area of flange	sq. in.
A_p	=	cross-sectional area of plate	sq. in.
A_w	=	cross-sectional area of web	sq. in.
a	=	distance below the top of hold frame to salt water	ft.
B	=	breadth of ship	ft.
b	=	distance from side shell to first girder support	ft.
C_1	=	moment coefficient	
D_s	=	depth of ship to strength deck	ft.
d	=	depth of double bottoms	ft.
e_i	=	'tween deck height	ft.
f	=	end fixation factor	
g	=	as subscript, refers to girder	
H	=	full load draft	ft.
h	=	head of salt water at midspan of the hold frame	ft.
I	=	moment of inertia of frame section	$in.^4$
K	=	slope of the elastic curve at the support, assuming simple end supports	
k	=	moment coefficient	
L	=	length of ship (waterline)	ft.
L_f	=	length of hold frame	ft.
ℓ	=	unsupported span of hold frame	ft.

ℓ_1	=	height of salt water above the top of the hold frame	ft.
M	=	bending moment	in. x lb.
m	=	fractional moment	
N	=	load numeral for deck beams	sq. ft.
NF	=	load numeral for hold frames	sq. ft. + lb.
n	=	number of standard 'tween deck heights	
P	=	total axial load acting on the cross-sectional area of the hold frame	lb.
P_{td}	=	axial load due to the 'tween deck loading	lb.
P_{md}	=	axial load due to main deck loading	lb.
r	=	least radius of gyration of cross-sectional area	in.
s	=	frame spacing	in.
s	=	as subscript, refers to side shell	
t	=	plating thickness	in.
t_w	=	wastage allowance	in.
w	=	intensity of lateral loading	lb. per ft.
σ'_b	=	allowable bending stress	psi
σ'_p	=	allowable compressive stress for axial loading	psi
σ_T	=	total stress as the sum of axial and bending stresses	psi
ρ	=	specific gravity of salt water taken as 64 pcf	pcf
α	=	slope of elastic curve	
β	=	slope of elastic curve	
Δ_x	=	inverse of the slope produced by a unit bending moment	

II ANALYSIS

Boundary Conditions

The strength analysis of complex structures such as illustrated in Figures II, III and IV is usually performed by separating the structure into simple elements upon which an individual study can be made. The solution for each simple element would be exact provided that the element is assigned boundary conditions which duplicate those existing at the joint with contiguous structure. Therefore in order to analyize a structural member such as a hold frame, it was deemed necessary to examine a few successful ship designs to determine values of relative stiffnesses* for the transverse structural members.

In (4), Hay lists a value of 0.96 for the relative stiffness of the double bottom and 0.04 for the lower end of the hold frame; this indicates that the lower end of the hold frame could reasonably be considered as clamped ($f = 1.0$). Vedeler (5) presents the "Method of Primary Moments" by which one may analyse a complex structure in terms of relative stiffnesses and relative values of lateral loading to determine the degree of fixation for all members meeting at a joint. The method is similar to the moment distribution method; it rapidly converges toward compatible fixations. The Method of Primary Moments is

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* Relative stiffness refers to the ratio of EI/ℓ between two adjoining members.

based upon the following limitations.

1. Consider only the distortion due to bending while neglecting the effects of shear and axial stress.
2. The material follows Hooke's Law.
3. The deflections are assumed to be small.
4. The structure and the loading are assumed to be symmetrical about the vertical centerline; therefore, no sidesway is permitted. The method could be modified to include the effects of sidesway as is done in moment distribution solutions.

Using the Method of Primary Moments, calculations were carried out for a transverse section of the C3-S-A2 and the Mariner cargo vessels; the latter calculation is included as Table 1 in Appendix B. Both calculations verified that the lower end of the hold frame may be considered as clamped, $f = 1.0$, while the average fixation for the upper end is $f = 0.50$. In this analysis an end fixation of $f < 1.0$ defines an end moment which is a fraction, f, of the respective end clamping moment.* An end fixation of $f = 1.0$ defines the end moment required for a zero slope of the elastic curve for a given lateral loading and/or for an applied bending moment at the opposite end.

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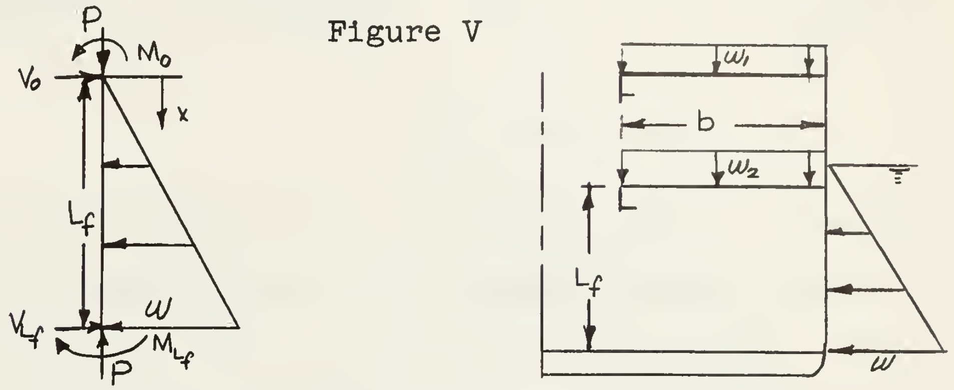
* The end clamping moments for a given distribution of lateral load are defined by a zero slope of the elastic curve at each end.

Design Loadings

The hold frame, as part of the vertical side frame, is subjected to various loadings, the most important being the uniformly varying lateral load.

Figure V



Principal Loadings Acting on Hold Frame.

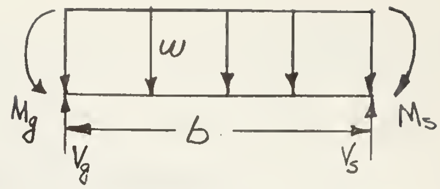
The frame also acts as a column in resisting an axial load due to the vertical loadings on the decks as illustrated in Figure V. There are other loadings on the frame which are usually considered secondary such as the effect of ship motions, temperature effects, and the possible interaction with longitudinal bending.

Axial Loading

From Figure V, it is apparent that the axial loading may be defined in terms of the uniform load acting on each deck. From Table 1 of Appendix B, the deck beams were found to have average end fixations of 0.56 and 0.95 at the hatch girder and side shell respectively. An analysis of the Rule requirements for deck beams by Rhyu (6) indicated end fixations of 0.50 and 0.85 for the same support conditions.

$$M_g = \frac{(.56)\ wb^2}{12} \qquad V_g = \frac{11.22\ wb}{24}$$

$$M_s = \frac{(.95)\ wb^2}{12} \qquad V_s = \frac{12.78\ wb}{24}$$



$f_g = 0.56$ and $f_s = 0.95$

Although these fixations lead to unequal end reactions as shown in the sketch above, this analysis assumes, as do the ABS Rules, that the end reactions are both $\frac{wb}{2}$. This results in a 6.5 per cent error in axial load or axial stress; however, in the design calculations it was found that the maximum error in axial stress would be about 300 lb. per sq. in. which is within the accuracy of the overall analysis.

References (1) and (3) state that the 'tween deck volume may be assumed to be loaded with a standard cargo density of 50 cu. ft. per long ton (44.8 pcf). Therefore, the axial load on a hold frame due to the 'tween deck loading acting over one frame space may be defined as;

$$P_{td} = (44.8)\ \tfrac{1}{2}\ \left(\frac{bs}{12}\right)\ (e_1 + e_2 + \cdots e_i) = (44.8)\ \tfrac{1}{2}\ \left(\frac{bs}{12}\right) \sum e_i \qquad (2)$$

The main deck loading is usually expressed in terms of a certain head of salt water. Reference (2) indicated that ABS requirements for strength deck plating were based on a head of 5.25 ft. The axial load on the hold frame due to this head may be defined as;

$$P_{m_d} = (5.25)\ (64)\ \frac{bs}{24} = 336\ \frac{bs}{24} \tag{3}$$

The Rules define the standard 'tween deck height to be 8.5 ft.; assuming this value for e_i , the total axial load acting on the hold frame may be defined for any number, n, of 'tween deck heights by combining equations (2) and (3).

$$P = P_{td} + P_{md} = (378n + 336)\ \frac{bs}{24} \tag{4}$$

Lateral Loading

In order to describe the moments due to the lateral loading, the span or length of the hold frame must be defined. From Figure VI - A, a hold frame length defined by

Figure VI

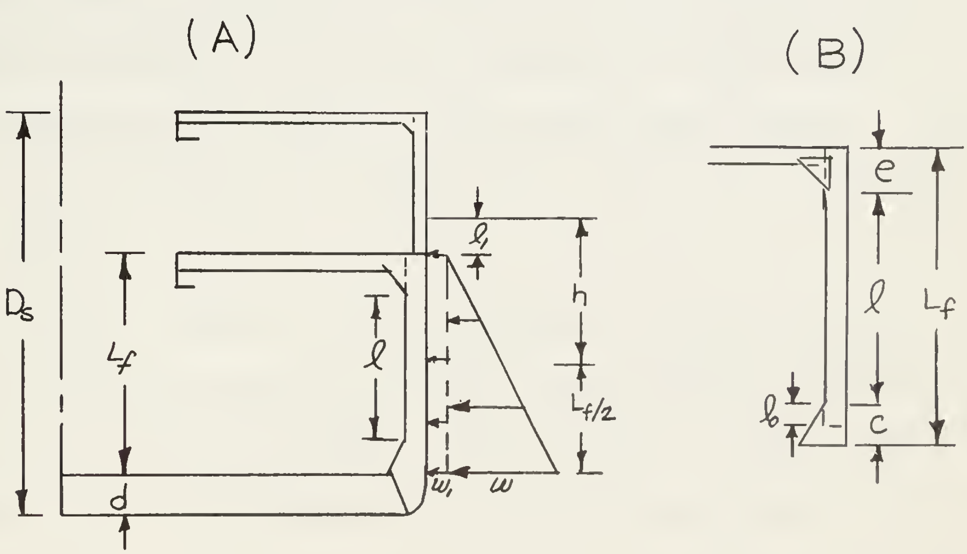


Illustration of Hold Frame Length for Lateral Loading.

L_f is a reasonable estimate for the extent of lateral loading upon which the hold frame scantlings should be based. For any number of 'tween deck heights, the hold frame length may be defined as;

$$L_f = D_s - d - 8.5n \tag{5}$$

In order to compare the results of the analysis with the strength requirements of the Rules, it was necessary to relate the hold frame length to the rule length or unsupported span, ℓ. Section 25, Table H of the Rules (1) requires that the overlap, ℓ_0, of the frame on the hold frame bracket shall not be less than $\ell/8$. The practice of using bracket lengths defined by one-eighth of the span is generally accepted when designing the scantlings for the field moment.* For the purpose of this analysis, it is assumed that the length of the hold frame bracket and the distance from the toe of the beam knee to the top of the hold frame are one-eighth of the hold frame length. Therefore, as illustrated in Figure VI - B, $e = c = L_f/8$ and $\ell = 0.75\ L_f$.

The end moments for a uniformly varying lateral load may be defined knowing that the end fixations are 0.50 and 1.0 at the top and bottom, respectively, of the hold frame. However, the scantlings of the hold frame should not be

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* The field moment is defined as the maximum bending moment along the span of the hold frame.

based upon either of these end moments since the beam knee and the hold frame bracket contribute additional stiffness at the ends. Instead, the scantlings should be based upon the field moment defined by the lateral load distribution with the above end fixations.

A lateral load distribution as illustrated in Figure VI - A can be defined by the superposition of a uniform load distribution, w_1, upon a uniformly varying load distribution, w. The respective loads per foot are;

$$w_1 = \rho s \ell_1 \qquad \text{and} \qquad w = \rho s L_f \qquad (6)$$

The field moment due to the superposition of these two loadings may be expressed as;

for $0 \leq \ell_1/L_f < 0.46$,

$$M = \frac{sL_f{}^2}{4.68} \left[7.5\, L_f + 15.6\, \ell_1 \right] \qquad (7)$$

for $\ell_1/L_f \geq 0.46$,

$$M = \frac{sL_f{}^2}{4.68} \left[7.2\, L_f + 16.25\, \ell_1 \right] \qquad (8)$$

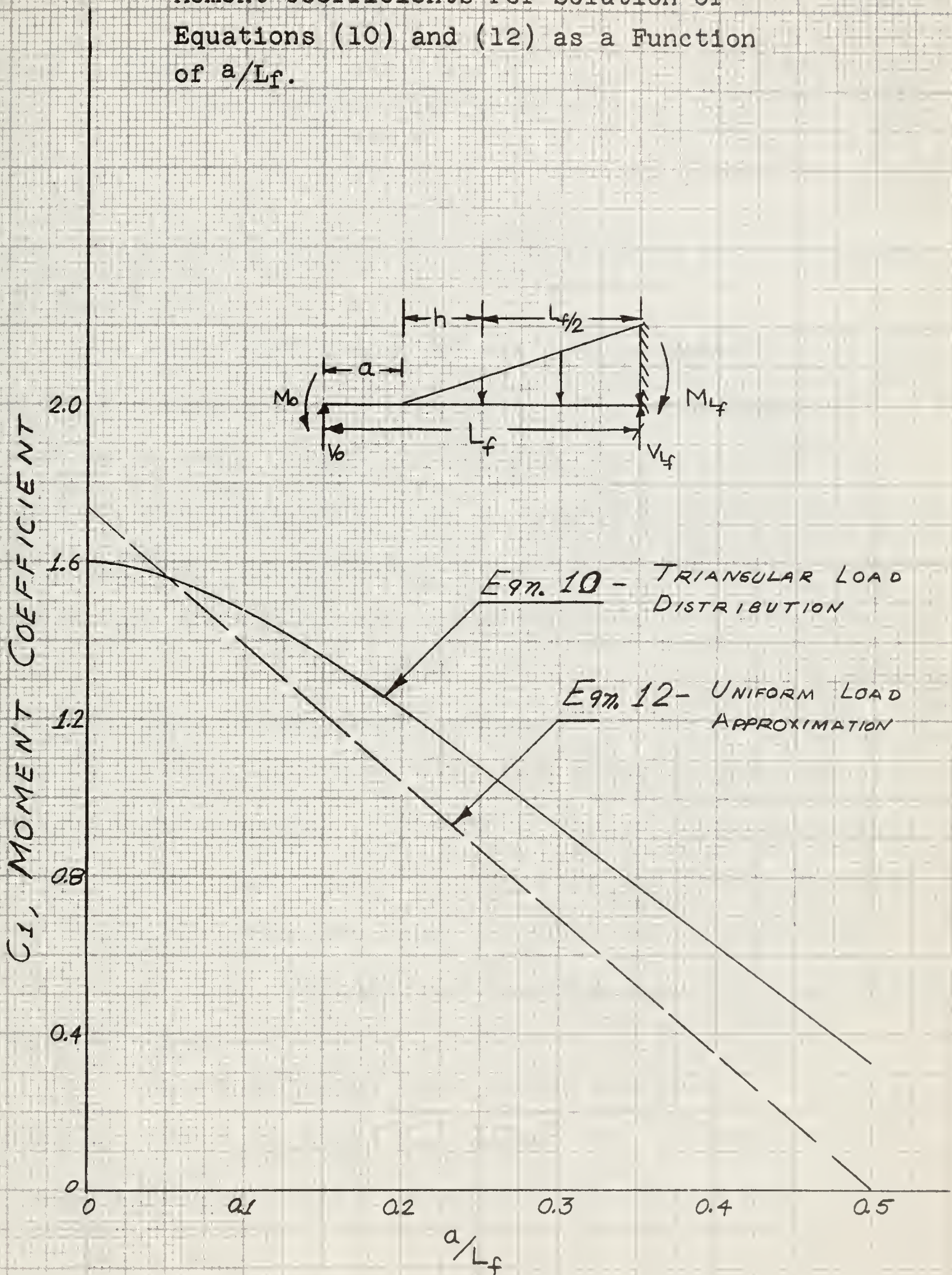
When the height of salt water is a distance "a" below the top of the hold frame, (corresponding to a negative ℓ_1 in Figure VI - A), the field moment relation becomes more complex than the above equations (7) and (8). The load per foot may be expressed as;

$$w = \rho s (L_f - a) = \rho s L_f (1 - a/L_f) \qquad (9)$$

In order to facilitate computations, the field moment may be determined for intervals of a/L_f, and the variation

Figure VII

Moment Coefficients For Solution of Equations (10) and (12) as a Function of $^a/L_f$.



plotted in terms of a moment coefficient, C_1.

$$M = C_1 sL_f^3 \tag{10}$$

Where

$$C_1 = \left(1-\frac{a}{L_f}\right)^4 \left\{15\frac{x}{L_f}\left(2+\frac{a}{L_f}\right)+6\frac{a}{L_f}-4\right\} - 6\frac{x}{L_f}\left(\frac{a}{L_f}\right)^5 - 40\left(\frac{x}{L_f}-\frac{a}{L_f}\right)^3$$

The variation of C_1 with a/L_f is plotted as the solid line in Figure VII.

The Rules define the lateral load in terms of the head above the midpoint of the unsupported span as shown in Figures II, III, IV and VI. References (7) and (8) also present this approximation of a triangular load distribution by a uniform load distribution defined by this head. Using the design end fixations, the field moment is defined as;

$$M = 3.465 \; sh \; L_f^2 \tag{11}$$

As the height of salt water becomes less than the height of the hold frame top, there will be a limiting value of a/L_f below which, equation (11) will not approximate the actual field moment. This condition is expressed in the Rules by the limitation that the head, h, shall not be less than $0.4\,\ell$. For this analysis, this limitation may be illustrated by rearranging equation (11) with $h = L_f\,(\frac{1}{2} - a/L_f)$.

$$M = 3.465 \; sL_f^3 \left(\tfrac{1}{2} - a/L_f\right) = C_1 sL_f^3 \tag{12}$$

Equation (12) is plotted as a broken line in Figure VII. The intersection of the two curves illustrates that, with

end fixations of 0.50 and 1.0, the uniform load approximation is only feasible for $a/L_f \leq 0.05$.

Design Considerations and Assumptions

The application of the design loading analysis and the associated calculations shall be based upon the scantlings for the series of welded inverted angles* given in Table 6 of the Rules. The Department of Naval Architecture at the Massachusetts Institute of Technology has developed section modulus curves for these inverted angles for wastage allowances of 0.05", 0.10", and 0.15" and for effective breadths of 30t, 40t, 50t, and 60t.

In (3) Brown reports that tests conducted in Great Britain indicated that the effective breadth of plating ranged from 45t to 55t. (t = plate thickness). The subsequent design calculations shall be carried out using various ship depths; Table 12 of the Rules defines the required side shell plating thickness for each ship depth. For the shallow depth ships, 40t is the largest available effective breadth which will define a width of plating which is less than the Rule frame spacing; therefore, the use of 40t will permit the use of the modulus graphs in all calculations. Actually, as Brown (3) points out, the

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* The scantlings of the welded inverted angles are obtained by removing the faying flange from channel sections without decreasing the overall depth of the section.

section modulus does not vary greatly with effective breadth for the usual plating thickness; this variation is also illustrated in the section modulus graphs in Appendix C for the region beyond the "knuckle" when the neutral axis is closer to the plating.

The structural adequacy of an inverted angle section for a given loading can be determined using the associated plate thickness to define the total area and to determine the section modulus from the graphs in Appendix C.

During the initial phase of design, the thickness, of the side shell plating may not be available for an analysis as above; in this case, the frame design might be based on the assumption of a balanced design.* An analysis of the 1960 ABS Rules for the transverse frames of tankers by Stirling (9) indicated that the required girder section moduli were based upon the use of a balanced design. The design calculations in Appendix D include the results for the use of a balanced design.

Equation (4) defines the axial load acting on the hold frame as a function of frame spacing and the span of the deck beam. For this analysis the standard frame spacing of the Rules shall be used to define the design

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* Balanced design refers to a symmetrical section where $A_f = A_p$. The neutral axis of the effective section is equidistant from the extreme fibers of the plate and flange; the "knuckle" in a section modulus graph defines this point.

loadings. $s = \frac{25\ L}{1000} + 17$ (13)

Table I

Approximation of Hatch Width

Design	L(ft.)	L/20(ft.)	Actual Hatch Width (ft.)
C-1-B	395	19.8	20
C-2	470	23.5	25
C-3	465	23.2	24
Mariner	528	26.4	30

Table I indicates that $L/20$ is a reasonable approximation for the hatch width; assuming no supporting members between the side shell and the hatch side girder, the deck beam span may be approximated by;

$$b = \tfrac{1}{2}\ (B - L/20) \qquad (14)$$

As the ship's beam increases, equation (14) would lead to spans which would ordinarily not be used in good design practice. Table 5 of the Rules defines a maximum span of 28 ft. from the hatch girder to the inner edge of the beam knee; therefore, allowing for the length of the beam knee, it shall be assumed that the maximum value of b is 30 ft..

$$b = \tfrac{1}{2}\ (B - L/20) \leq 30 \text{ ft.} \qquad (15)$$

Section 2 of the Rules (1) states that the maximum beam considered by the Rules is twice the depth to the

strength deck. The use of $B = 2\,D_s$ in the analysis would define one of the more severe design conditions for the axial load defined by equation (15).

The applicability of the basic design procedure will be tested by using three values of ship depth, D_s, for each ship length. Using the standard 'tween deck height of 8.5 ft., the length of the hold frame is then dependent upon the number of 'tween decks and the depth of the double bottom.

In Table 4 of the Rules, the depth of the double bottoms is dependent upon both L and B, and may be expressed as;

$$d(\text{in.}) = \frac{L}{20} + 18 \qquad \text{or} \qquad d(\text{in.}) = B-20$$

The design depth is then based on the expression requiring the greatest depth. For this analysis, the calculations for the various depths will be based on the following double bottom depths;

D_s (ft.)	d (in.)
Shallow $\left(\frac{7L}{100}\right)$	$\frac{12\,D}{10}$
Intermediate $\left(\frac{7L}{100} + 7\right)$	$\frac{L}{20} + 18$
Deep $\left(\frac{L}{10} + 7\frac{1}{2}\right)$	$B - 20$

The number of 'tween decks selected for any value of ship depth and associated depth of double bottom shall be arbitary. The only restrictions placed on the number of

'tween deck heights shall be the following.

1. The resultant $L_f \geq (\frac{4}{3})$ 7 ft. to satisfy the Rule requirement that $\ell \geq$ 7 ft.
2. The resultant $L_f \leq$ 40 ft., since the Rules define ℓ_{max} = 30 ft.
3. The resultant combination of ℓ and NF shall be within the limits of Table 6 of the Rules.

Design Strength Criteria

1. The adequacy of the hold frame sections under combined axial and lateral loadings may be determined by relating the sum of the axial and bending stresses to the yield strength of the material. The analysis has neglected the effects of secondary loadings which in some cases might require further consideration; therefore, a rational stress criterion would limit the axial and bending stresses to σ_y/1.25. For mild steel, this would define an acceptable total stress as;

$$\sigma_T = P/A + M/Z \leq 27{,}000 \text{ psi} \tag{16}$$

The field moment on the hold frame should not be based solely on the full load draft; the influence of actual wave conditions can be approximated by using an increased draft. The L/20 wave height is widely used in merchant ship design to approximate this additional draft due to waves. The bending stress will be determined for both the full load draft as defined by the Rules and the full load draft plus the crest of a L/20 wave height.

2. Structural design for merchant ships is usually based upon the use of a wastage allowance to compensate for loss of material effectiveness due to corrosion, etc. Studies such as (2) indicate that the wastage allowance varies for the different structures in a ship. The design calculations shall consider wastage allowance ranging from 0 to 0.15 in.; the wastage allowance which satisfies the total stress criterion should hopefully be some where in the range of 0.07" to 0.11".

3. The structural analysis of a column type structure such as a hold frame should consider the effects of buckling. The interaction formula,

$$\frac{P/A}{\sigma p} \quad \frac{M/Z}{\sigma b} \leq 1.0 \tag{17}$$

is used by many designers to limit the combined stresses by the use of allowable stresses, σp and σb. Since the bending stress is only a line stress, the allowable σp is usually about 27,000 psi. The axial stress, however, is an area stress, and therefore, the allowable σb is expressed as a function of the slenderness ratio, ℓ/r, by the well known Euler and Moncrieff formulas. Equation (17) can be rearranged to define the allowable compressive stress.

$$\sigma p = P/A \left[\frac{1}{1 - \frac{M/Z}{27,000}} \right] \tag{18}$$

Using the design calculations, the values of σp versus ℓ/r may be obtained and compared with the

Euler - Moncrieff relation or any other suitable column design relation.

Method of Calculation

The calculations shall be carried out using the following steps for each value of ship length.

1. The basic ship scantlings and the full load draft will be obtained from the ABS Rules as a function of ship length.

   D_s d

   $B = 2\ D_s$ t_s

   s H

2. Calculate the following for the assumed number of 'tween deck heights.

   L_f h

   ℓ b

3. A suitable hold frame section shall be selected from Table 6 using

   $$NF = \frac{s}{12}\left[h + \frac{h_1 b}{100}\right] \quad \text{and}$$

   The height $h_1 = 8.5n + 8$ when the bulkhead deck may be considered as the strength deck; otherwise $h_1 = 8.5n$.

4. Tabulate the total area and section modulus for the section for each wastage allowance using the graphs in Appendix C.

5. Determine the axial load and the field moment. Tabulate the stresses as a function of wastage allowance.
6. Using the results of step 5, determine the allowable compressive stress and the associated slenderness ratio for the desired wastage allowance.

III RESULTS

Design calculations based upon the analysis of Section II produced the following results for end fixations of 0.5 and 1.0.

Uniformly Varying Lateral Load

1. A wastage allowance of 0.10 in. defined total stresses of 13,700 psi for the full load draft and 26,500 psi for the full load draft increased by an L/20 wave height. Figure VIII presents these results; the representative total stresses were obtained by the method of least squares.
2. The total stress for a balanced design with an 0.10 in. wastage allowance was 21,000 psi for the full load draft. Stresses for the increased draft due to an L/20 wave were, for the most part, greater than the yield stress; therefore, they were not included in Figure IX. The total stress may be more accurately represented by the relation, $\sigma_T = 15L + 13{,}500$.
3. The allowable compressive stresses for an 0.10 wastage allowance reasonably approximate the various column design formulas as illustrated in Figure XI. The associated values of the slenderness ratio are within the range of 30 to 50.

Uniform Load Approximation

For an 0.10 wastage allowance, the uniform load approximation defined total stresses of 14,300 psi and 27,500 psi corresponding to the stresses, 13,700 psi and 26,500 psi respectively, obtained from the actual distribution of lateral load.

Figure VIII

Total Stress v.s. Ship Length for a Uniformly Distributed Lateral Load.

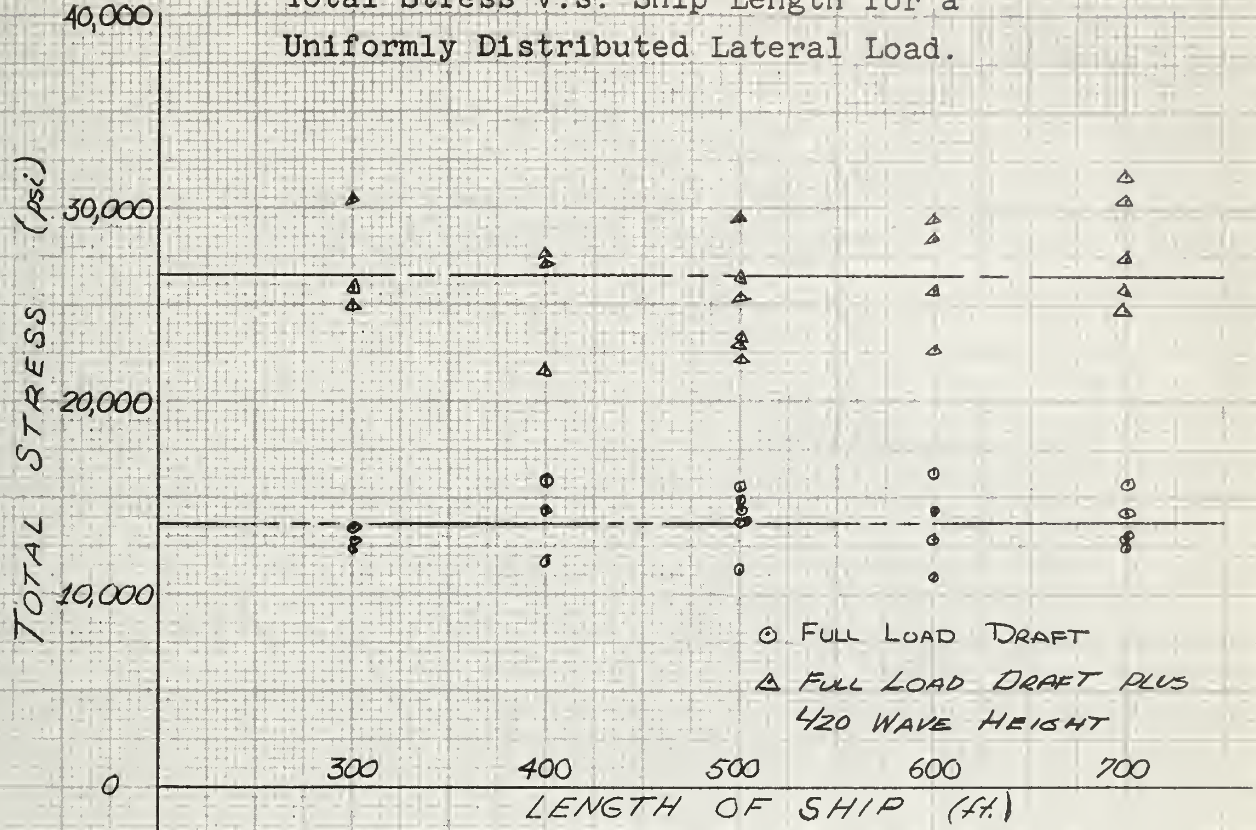


Figure IX

Total Stress v.s. Ship Length for a Uniformly Distributed Lateral Load Assuming Balanced Design.

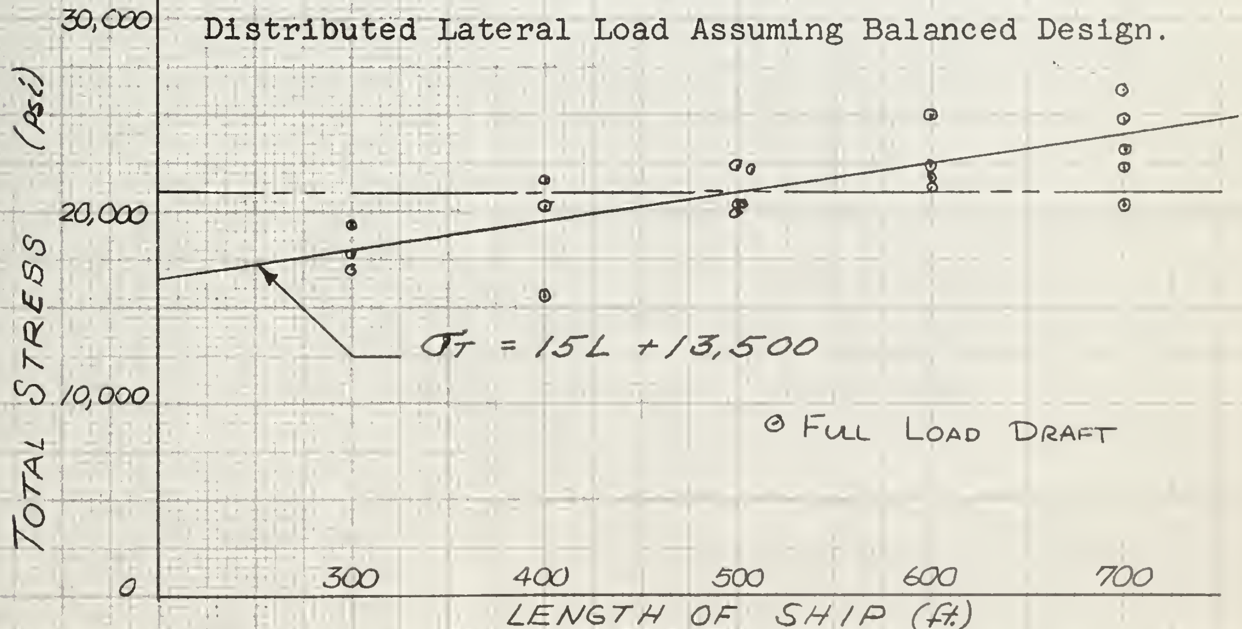


Figure X

Total Stress v.s. Ship Length for the Uniform Load Approximation of the Lateral Load.

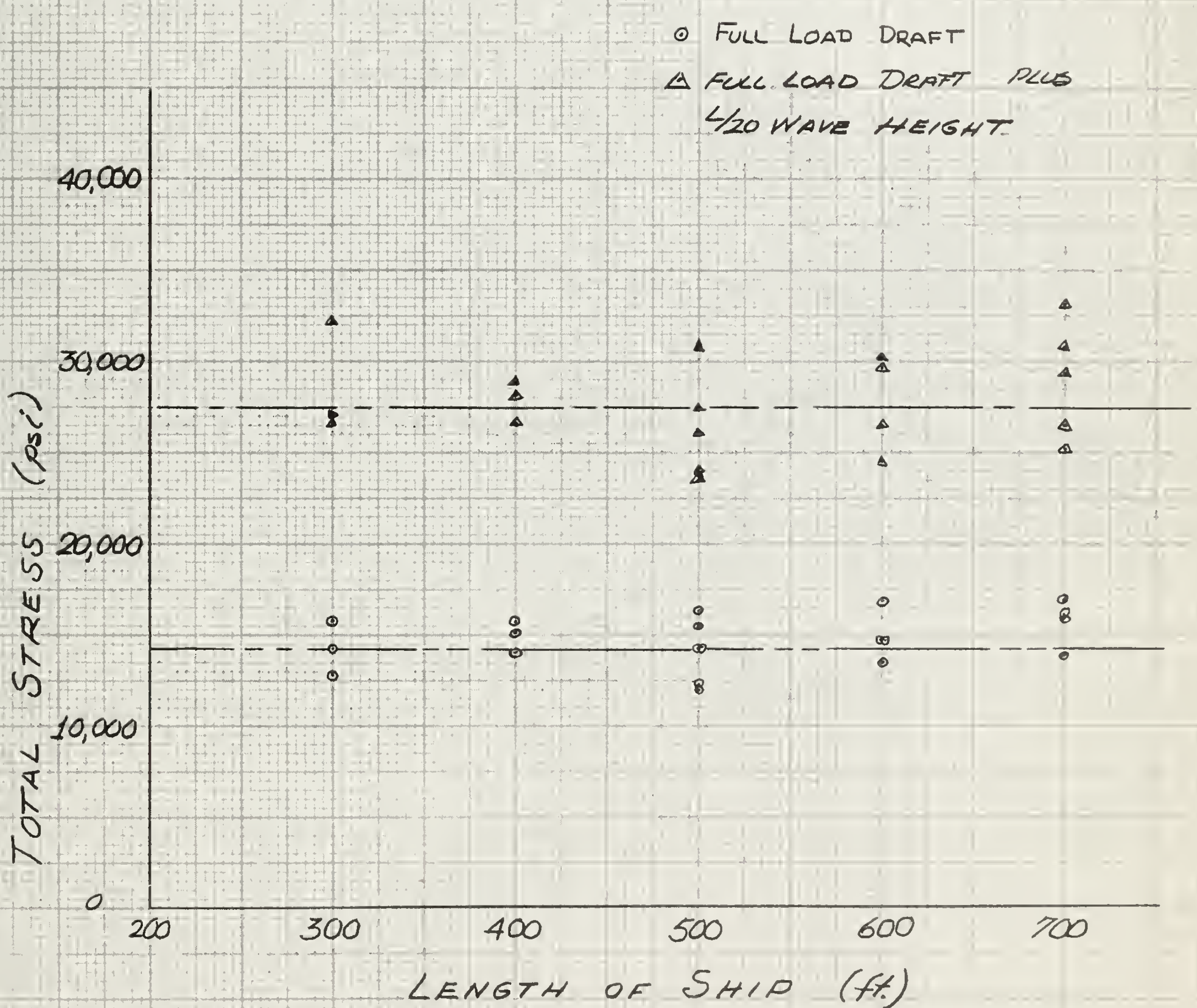
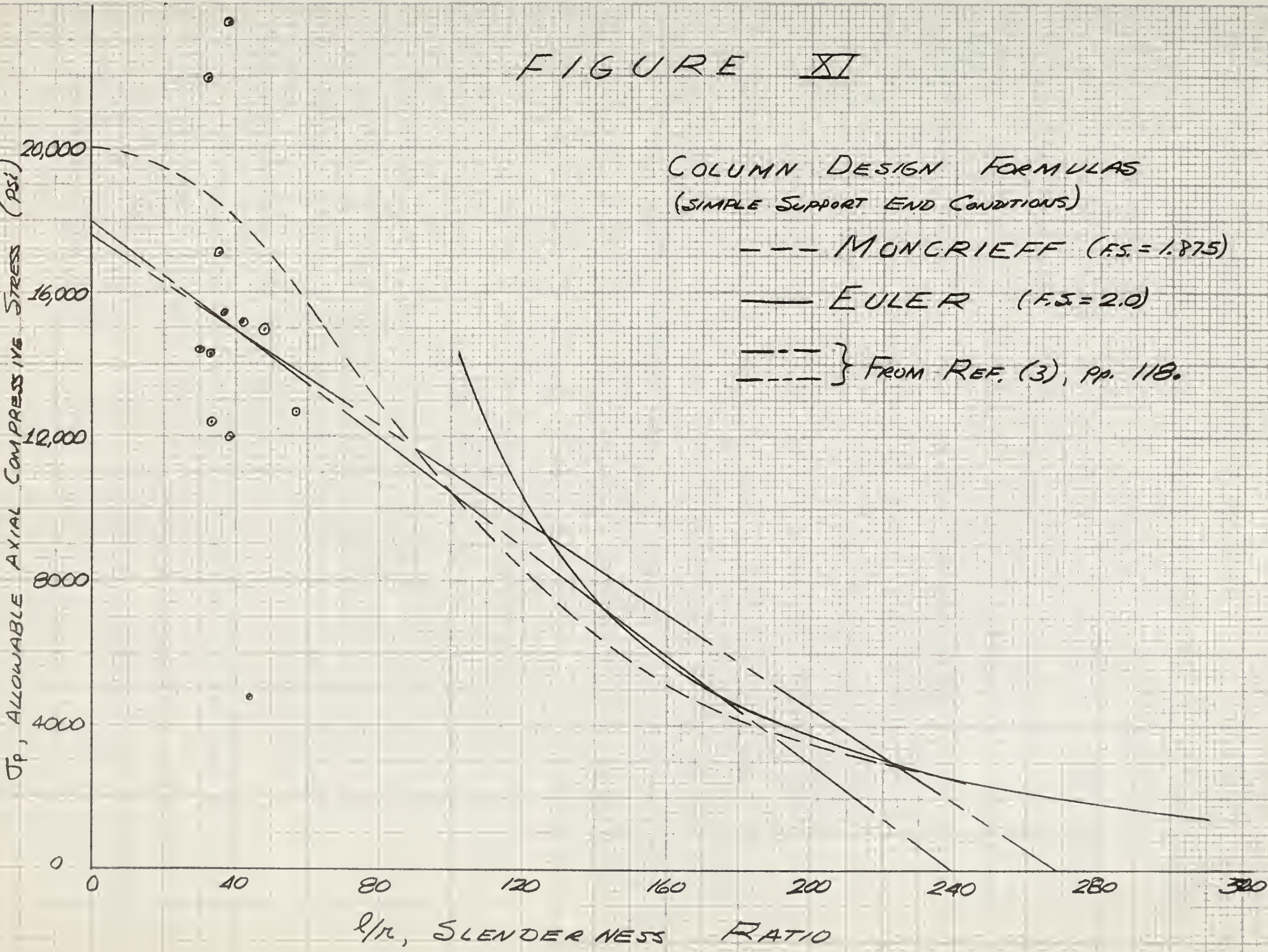


FIGURE XI



COLUMN DESIGN FORMULAS
(SIMPLE SUPPORT END CONDITIONS)
MONCRIEFF (F.S. = 1.875)
EULER (F.S. = 2.0)
FROM REF. (3), pp. 118.
20,000
16,000
12,000
8000
4000
0
0
40
80
120
160
200
240
280
320
σ_p, ALLOWABLE AXIAL COMPRESSIVE STRESS (PSI)
l/r, SLENDERNESS RATIO

IV Discussion of Results

Hold Frame Length and End Fixations

The importance of a rational definition for the hold frame length should not be underestimated. The length defines the extent of the lateral loading and, therefore, the magnitude of the field moment which largely controls the selection of the hold frame scantlings. The selection of proper end fixations is also dependent upon the definition of hold frame length, and it is this latter dependence that is probably the most important.

The fixation study, based on a hold frame length as the vertical distance from the double bottom floor to the lowest deck, indicated fixations of 0.50 and 1.00 for the top and bottom respectively. These are felt to be reasonable fixations for the influence of contiguous structural members found in actual practice.

Appendix B describes several attempts to define end fixations for the unsupported span of the hold frame; for the most part, these were inconclusive. One exception was for $\ell = 3/4\ L_f$ and end fixations of 0.0 and 0.5; the field moment closely approximated the field moment based on L_f and fixations of 0.5 and 1.0.

Future research could be directed toward the analysis of the side frame and deck beams as a complete structure to compare the resultant end moments (or implied end fixations) to those developed in this thesis.

Lateral Loading

The sample calculations in Appendix D demonstrate that the field moment due to the lateral loading, primarily, determines the required scantlings for the hold frame. As mentioned above, the field moment is dependent upon the length of the hold frame.

After the selection of the number of standard 'tween deck heights for a particular ship depth, the length of the hold frame is dependent only on the depth of the double bottoms. For each of the three ship depths investigated, a relation for the associated double bottoms depth was specified by what was felt to be a reasonable variation. If, instead, only one variation of depth of double bottoms had been used for all ship depths, the lengths of the hold frame, in most cases, would have been changed. However, the factors used to select a suitable section from the Rules would also have changed; and it is felt that the new section would have about the same value of total stress as did the original section. This can be illustrated by two calculations for a ship length of 700 ft.; the relation used for the intermediate depths defined the same depth as the shallow depth given in Table 12. However, from Section II, the double bottom depths are determined by different relationships.

Table II

Variation of Depth of Double Bottoms

D_s = 49'	n	d	L_f	ℓ	NF	Section
Intermediate	4	4.4	17.6	13.7	77.6	15" x 3.52"
Shallow	4	5.6	16.4	12.15	76	13" x 4.00"

M/z	σ_T
22,100	24,670
27,500	30,300

Table II exhibits the effect of varying the depth of the double bottoms. Although the values of total stress differ by over 5,000 psi, it should be pointed out that this is less than the extreme variations found in Figure VIII.

Another point illustrated in Table II is that the factors used in selecting sections from Table 6 of the Rules, that is ℓ and NF, do not differ greatly; therefore, the section for the intermediate depth should be the next largest available section following the 13" x 4.00" angle section; this in fact is the 15" x 3.52" angle section. The ratio of section modulii for the two sections, t_w = 0.10 in., is 1.45; however, the ratio of field moments for the deepest draft relation is only 1.18.

From the discussion of Table II, the following conclusions can be drawn.

1. For a particular ship depth and a designated number of 'tween deck heights, the length of the hold frame

(and the field moment) is dependent upon the depth of the double bottoms. Appropriate hold frame scantlings could be selected, assuming they are available, for any reasonable combination of L_f and d, such that the total stress just satisfies the design stress criterion. This is the essence of structural design.

2. The extremes of variation in total stresses for any one value of ship length are due in part to the limited number of angle sections available for design calculations.

Lateral Loading as Defined by the ABS Rules

The Rules define the lateral load on the hold frame in terms of the head acting at the midspan of the frame. This analysis has assumed that the Rules approximate the actual triangular load distribution with a uniform load distribution defined by the above mentioned head.

For multi-deck ships, the uniform load approximation is reasonably accurate; this is verified by comparison of Figure X with Figure VIII. For deep cargo holds or deep tanks where the height of salt water is below the top of the hold frame, the uniform load approximation is not an accurate representation for the field moment.

The total stresses defined by the uniform load approximation also exhibit quite a variation for each particular ship length. As mentioned previously, part of

this variation can be attributed to the lack of a sufficient number of sections. Another factor which could influence the results and cause variations in total stress is the design practice of the ABS.

Rhyu (6) examined the required strength of deck beams using the same inverted angle sections as utilized in this analysis. Using Table 5 of the Rules, Rhyu expressed the bending moment in terms of an average $(N)\ell^2$ for each particular angle section. In the case of hold frames, it is not appropriate to use $(NF)\ell^2$ to represent a bending moment since the load numeral, NF, is also a function of axial load. However, it was found that, for any particular angle section, the average values of $(N)\ell^2$ and $(NF)\ell^2$ were equal; a tabulation of these average values is included in Appendix C for the respective sections.

It seems reasonable to assume that the average value of $(NF)\ell^2$ for any particular hold frame section defines the total stress (or required strength) consistent with some design practice or design stress used by the ABS. Many of the $(NF)\ell^2$ combinations approximate this average value; however, there are combinations which are both larger and smaller than this average value. Under this assumption, the ABS Rules do consider and accept hold frame sections which have larger, as well as smaller, total stresses than the design limit; there would be, of course, a reasonable limit for this variation

consistent with prohibitive overloading and uneconomical use of material respectively. Since the design analysis developed in this thesis is being compared with the Rule requirements, it seems reasonable to conclude that some of the variation in total stresses in Figures VIII, IX and X is due partly to a reflection of variations within the Rule requirements.

The object of this analysis was not to study the ABS Rules in an attempt to determine their design procedure; however, since comparison of a proposed design analysis with the requirements of the Rules is the nearest thing to actual construction, it was necessary and desireable to analyse some of the hold frame requirements of the Rules. Further studies of the ABS Rules should be considered using the results and assumptions of this analysis.

Axial Load and Allowable Compressive Stress

The axial load acting on the hold frame can be expressed as a straightforward function of the deck loadings. It is rather difficult to evaluate the effect of the assumptions made concerning the axial load since the total stress is comprised of only ten to fifteen per cent as axial stress.

The interaction formula is felt to be a better representation of column adequacy than the total stress criterion since the axial stress is treated somewhat separately. The influence of buckling upon the adequacy of the hold frame is introduced through the use of an allowable

compressive stress which is a function of the slenderness ratio of the member. Rearranging the interaction formula, the allowable compressive stresses were determined from the design calculations for an 0.10 wastage allowance. Figure XI indicates that the design analysis does define values of allowable compressive stress which are consistent with established column design formulas.

It should be pointed out that the treatment of buckling by the interaction formula and column design formulas based on simple end supports are accepted design practice; however, it is recommended that the buckling of hold frames as well as other structural members be the subject of further study using the available knowledge of buckling theory as presented in (10).

Balanced Design

The assumption of a balanced section is a practical, though conservative, method of structural design; using suitable design criteria, the hold frame could be sized without requiring the thickness of the side shell plate. The results of this analysis were somewhat disappointing since the total stresses for the draft increased by an L/20 wave height exceeded the yield stress.

Assuming a constant total stress, the method of least squares defined a value of 21,000 psi with an 0.10 wastage allowance for the full load draft. Associating this total stress to the yield stress, the design criterion

might well be $P/A + M/Z = \sigma y/1.5$ for balanced design. In the actual design, the effective plate area could increase the overall section strength and, therefore, enable the section to resist the increased draft due to an L/20 wave height.

The results of Figure IX differed from Figures VIII and X in that there is a decided increase of total stress with ship length; a reasonable approximation to the variation is $\sigma_T = 15L + 13{,}500$. This variation with length is surprising and somewhat doubtful. Reference (2) indicates that for ship bending stress based on an L/20 wave height, the stress values are low for short ships and high for long ships. This might be offered as a possible explanation in this case; however, the lack of any such variation in Figures VIII and X for the full load draft renders this explanation as implausible.

It is concluded that the use of a balanced section for the initial structural estimates of hold frames should limit the maximum total stress due to full load draft to $\sigma y/1.5$. Subsequent analysis should utilize the side shell plating thickness to determine the adequacy of the section for the increased head due to an L/20 wave height.

Applications of the Design Analysis

The end fixations of 0.50 and 1.0 for the hold frame lead to a design procedure which is concluded to be rational

and complete. Given the basic ship scantlings, full load draft, and the proposed 'tween deck heights, the required hold frame scantlings may be determined; the effects of changing any of these parameters can be quickly estimated by further calculations.

With the increasing use of digital computers in the field of Naval Architecture, the structural design of transversely framed ships through the use of a suitable program can be visualized. The development of a suitable program must be based on analyses such as (2) for longitudinal strength and analyses such as developed in this work for the transverse strength of the secondary structural members. To this end, the analysis of other secondary structural members is recommended.

V CONCLUSIONS

The end fixations of 0.50 and 1.0 for the hold frame lead to a design procedure which is concluded to be rational and complete. The comparison of the design analysis with the requirements of the ABS Rules produced values of wastage allowance, total stress, and allowable compressive stresses which are reasonable and consistent with good design practice.

The uniform load approximation based on the head of salt water acting at the midspan of the hold frame is a reasonably good design approximation as long as the depth of salt water is not below the top of the hold frame.

The use of a balanced section for design should be limited to preliminary structural estimates based on the full load draft.

The hold frame length (and the extent of lateral loading) should be the distance from the top of the double bottoms to the lowest deck.

The extremes in variation of total stress are due to the lack of a sufficient number of sections for the calculations and to the variations in ABS design practice.

VI RECOMMENDATIONS

The analysis has been concerned primarily with hold frames; the remaining members of the side frame, the 'tween deck frames, can presumably be sized by reducing the hold frame scantlings as some function of 'tween deck height. It is recommended that further study be directed toward verifying this practice with the requirements of the Rules.

Further research could be directed toward an analysis of the side frame and associated deck beams as a complete structure to compare the resultant end moments (or implied end fixations) with those developed in this work and in (6).

Other secondary structural members such as web frames, side stringers, bulkhead stiffeners and deck beams should be submitted to an analysis similiar to that used in this work; such design analyses, when combined, would enable the designer to formulate a design procedure for the structural design of transversely framed ships.

It is recommened that the buckling of hold frames as well as other secondary structural members be the subject of further study using the available knowledge of buckling theory. A detailed study of buckling would necessitate an evaluation of the contributions of secondary loadings.

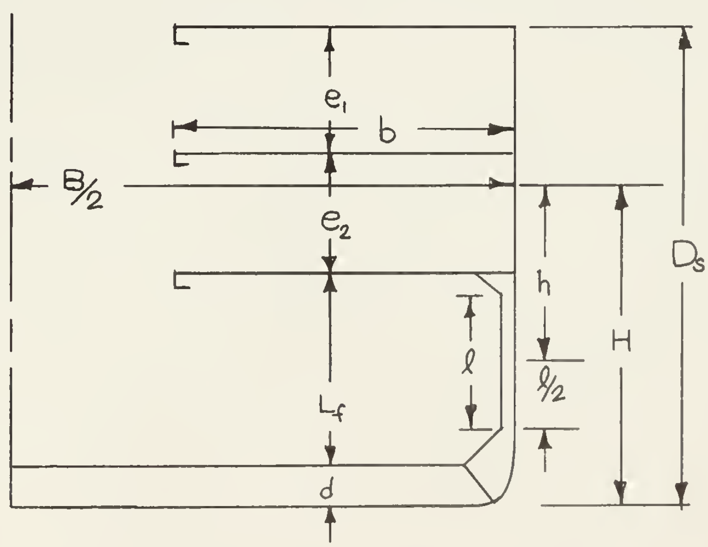
VII A P P E N D I X

APPENDIX A - INTRODUCTION

These appendices are devoted primarily to the presentation of the steps taken during the analysis of hold frames to develop the final design procedure. As in many structural analyses, there were the usual "blind alleys" and unfruitful procedures; these shall be mentioned and their results presented not only to steer future studies away from the seemingly unrewarding procedures; but also to point out the existence of such procedures for the more ingenious researcher.

The analysis and design procedure is developed for the hold frame as a member of a typical transverse section as shown in figure 1.

Figure 1



Typical Transverse Section

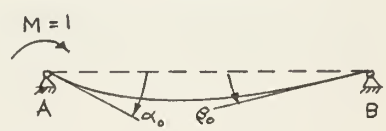
The various classification societies also treat the hold frame as the most important member of the side frame; the ABS Rules size the 'tween deck frames through the use of a numeral which is dependent only on ship length, L, and vertical location of the frame. In the Rules, the selection of scantlings for the hold frame is based upon the lateral load due to a water pressure of head h, an axial load due to the deck loadings above the frame, and the unsupported span length, ℓ , of the frame.

APPENDIX B - DETAILS OF ANALYSIS

Fixation Study

The hold frame as a member of a complex structure can be subjected to a reasonably accurate structural analysis only if appropriate boundry conditions or end fixations are utilized. In (4) Hay gives relative stiffness factors of 0.96 and 0.04 for the double bottom and hold frame respectively; this indicates that the lower end of the hold frame can be considered as clamped (f = 1.0) by the double bottom structure. In order to evaluate the fixation at the upper end of the hold frame, the Method of Primary Moments was utilized to study the fixation of actual designs. The Method of Primary Moments as presented by Vedeler in (5) enables the analyst to determine approximate end fixations using relative stiffness factors and relative magnitudes of loading.

The Method of Primary Moments is basically an application of the moment distribution method of analysis utilizing the relative stiffnesses of members to determine the fractional moment,* m, at the ends of the members. For a simply supported beam subjected to a couple M = 1 at the left support, the fractional moment is; $m_B = \beta_0/\alpha_0$ (1)



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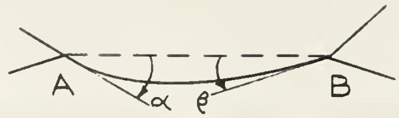
* In moment distribution notation, the fractional moment is termed the carry-over factor; viz., for a fixed support, $m = \frac{1}{2}$ and for a simple support, m = 0.

When other arbitrary structural members are connected to the ends of member AB, the slopes may be defined as;



$$\alpha = \alpha_0 - m_B \beta_0$$
$$\beta = \beta_0 - m_B \alpha_0 \tag{2}$$

The fractional moment m_B is;

$$m_B = \beta \sum \Delta_x \tag{3}$$

Δ_x for any one of the members connected to joint B is defined as the inverse of the slope produced by a unit bending moment acting on that end of the member.

Combining (2) and (3) gives;

$$m_B = \frac{\beta_0 \sum \Delta_x}{1 + \alpha_0 \sum \Delta_x} = \frac{(m_B)_{max.}}{1 + 1/\alpha_0 \sum \Delta_x} \tag{4}$$

Equation (4) is applicable to all kinds of beams; however, for straight beams with a constant moment of inertia, $\alpha_0 = \frac{l}{3EI}$ and $\beta_0 = \frac{l}{6EI}$ giving (m_B) max $= \frac{1}{2}$ and the fractional moment at B is;

$$m_B = \frac{1}{2 + \frac{6EI}{l \sum \Delta_x}} \tag{5}$$

From the above slopes, the expression for $\sum \Delta_x$ may be derived as;

$$\sum \Delta_x = 6E \sum \frac{I_x}{l_x (2 - m_x)} \tag{6}$$

The value of m_x is defined as the fractional moment at the other end of the member of length l_x and I_x. Combining equations (5) and (6) one can define;

$$m_B = \frac{N_B}{6 + 2N_B}$$

Where:

$$N_B = \frac{l \sum \Delta_x}{EI} = 6 \frac{l}{I} \sum \frac{I_x}{l_x (2 - m_x)} \tag{7}$$

With structures having no closed circuit of members, the

calculation of fractional moments may be made directly by starting at supports where the end conditions are known or can be reasonably approximated. After about three cycles the values of m become reasonably constant.

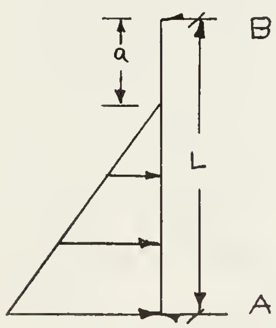
The degree of end fixation may be calculated using the results of equation (7). For members subjected to a uniformly distributed loading (or any symmetric loading);

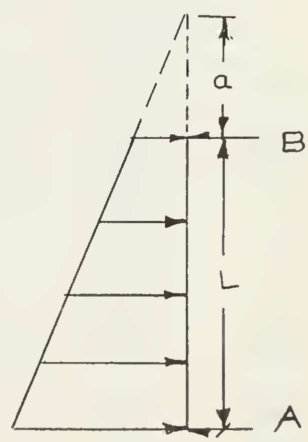
$$f_B = \frac{3\, m_B\, (1 - m_A)}{1 - m_A\, m_B} \quad \text{and} \quad f_A = \frac{3\, m_A\, (1 - m_B)}{1 - m_A\, m_B} \qquad (8)$$

For side frames subjected to a uniformly varying lateral load, the end fixations are defined as;

$$f_B = \frac{3 m_B}{1 - m_A m_B} \cdot \frac{1 - \frac{K_B}{K_A} m_A}{2 - K_B/K_A} \qquad (9)$$

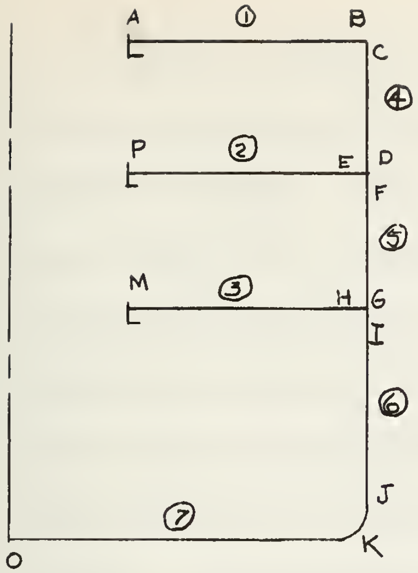
$$f_A = \frac{3 m_A}{1 - m_A m_B} \cdot \frac{1 - \frac{K_A}{K_B} m_B}{2 - K_A/K_B}$$





$$\frac{K_A}{K_B} = \frac{10L^2 - 3(L-a)^2}{20L^2 - 15L(L-a) + 3(L-a)^2}$$

$$\frac{K_A}{K_B} = \frac{7L + 15a}{8L + 15a} = \frac{\frac{7}{15}\frac{L}{a} + 1}{\frac{8L}{15a} + 1}$$



MIDSHIP Section of Mariner Cargo Vessel.

TABLE 1

Member	I/ℓ $\left(\frac{in^4}{ft}\right)$	Member End	Relative Stiffness
1	9.23	BA	0.36
2	6.68	CD	0.64
3	17.0	DC	0.15
4	17.2	EP	0.38
5	21.3	FG	0.47
6	27.66	GF	0.323
7	1320.0	HM	0.258
		IJ	0.419
		JI	0.02
		KO	0.98

Note: The moment of interia was calculated using the effective breadth of plating as 40t or the frame spacing, whichever was least.

Joint End	ℓ/I $(in^3)^{-1}$	Relations for N.	Final N	m	f
A	1.30	$\frac{6}{(2-m_B)}$	3.48	.269	.582
B	1.30	$\frac{11.16}{(2-m_D)}$	6.69	.345	.835
C	.698	$\frac{3.22}{(2-m_A)}$	1.865	.192	
D	.698	$\frac{2.33}{(2-m_P)} + \frac{7.44}{(2-m_G)}$	5.9	.331	
E	1.795	$\frac{15.4}{(2-m_C)} + \frac{19.1}{(2-m_G)}$	20.13	.435	1.07
P	1.795	$\frac{6}{(2-m_E)}$	3.83	.281	.542
F	.563	$\frac{4.84}{(2-m_C)} + \frac{1.88}{(2-m_P)}$	3.776	.279	.67
G	.563	$\frac{4.8}{(2-m_M)} + \frac{7.8}{(2-m_J)}$	7.99	.363	.79
H	.705	$\frac{7.5}{(2-m_F)} + \frac{9.77}{(2-m_J)}$	10.85	.392	.955
M	.705	$\frac{6}{(2-m_H)}$	3.73	.277	.567
I	.433	$\frac{4.62}{(2-m_F)} + \frac{3.69}{(2-m_M)}$	4.82	.308	.66
J	.433	$\frac{2860}{(2-m_K)}$	1440.	.499	1.25
K	.0091	$\frac{0.126}{(2-m_I)}$	.0745	.012	0.035

Table 1 indicates the results of the application of the above mentioned method to the midship section of the Mariner design. The fixation at the lower end of the hold frame, f_J, is greater than 1.0 which indicates that the greater stiffness of the double bottom structure is tending to rotate the lower end of the hold frame against the lateral water pressure loading. Such a condition would reduce the field moments due to lateral loading; further investigation of these results would be required before justifying the use of $f > 1.0$ for an analysis. Instead, the use of $f_J = 1.0$ seems to be in order and certainly is based on firmer ground by being more conservative. Calculations as in table 1 were also carried out for the C3-S-A2 cargo vessel; the resulting fixation values for the hold frame were: $f_J = 1.3$ and $f_I = 0.40$. The fixation for the upper end of the hold frame, can not be definitely defined after only two such calculations; however, the object of this study was to determine a reasonable value which could be used in the analysis. The selection of $f = 0.50$ for the upper end of the hold frame was made on this basis.

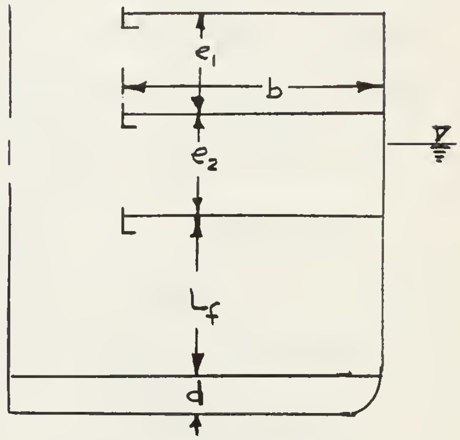
Design Loading

The hold frame, as part of the vertical side frame, is subjected to various loadings, the most important being the uniformly varying lateral load. The frame also acts as a column in resisting the vertical loads on the

decks. There are other loadings on the frame which are not readily evaluated such as the effect of ship motions and the possible interaction with longitudinal bending.

The axial load on the hold frame may be defined in terms a uniform load acting over a width equal to the frame spacing, s, and on a span length b. Table 1 indicates that the deck beams have average end fixation of 0.56 and 0.95 at the hatch girder and side shell respectively. Although this leads to unequal end reactions as shown in the sketch below, further analysis will be based on the approximation that the reactions are equal.

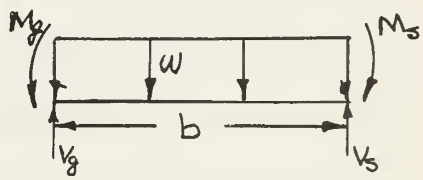
Figure 2



Typical Section for Design Loadings

$$M_g = \frac{(.56)\,w\,b^2}{12} \qquad V_g = \frac{11.22\,w\,b}{24}$$

$$M_s = \frac{(.95)\,w\,b^2}{12} \qquad V_s = \frac{12.78\,w\,b}{24}$$



Therefore, the hold frame is assumed to carry an axial load equal to one-half the deck load acting over an area = b x s.

Brown (3) states that generally "it is assumed that for all decks in way of cargo spaces, storerooms, baggage rooms, etc., the space above the deck can be loaded to its full molded volume with cargo or stores having a density of 50 cu. ft. per long ton". Therefore, due to

the 'tween deck loadings, the axial load on the hold frame may be defined as;

$$P_{td} = \frac{2240}{50}\left(\frac{b}{2} \times \frac{s}{12}\right)\sum e_i = 44.8\left(\frac{bs}{24}\right)\sum e_i \tag{10}$$

The design deck load for the main deck is usually expressed in terms of a certain head of salt water. Reference (2) indicated that ABS requirements for strength deck plating were based on a head of 5.25 feet; this would define a deck loading of 336 lbs. per sq. ft.. The Rules define the axial load on the hold frame in terms of 'tween deck height, h_1 as defined in Section I, page 5, of this thesis. The Rules require that when the bulkhead deck coincides with the strength deck the height of 'tween deck loading shall be increased by 8 feet; this is probably a means of defining a deck load of (8) (44.8) = 358 lbs. per sq. ft.. On the other hand, when the bulkhead deck is below the strength deck, the 'tween deck height above the bulkhead deck would exceed 8 feet, and the axial load would be defined by only the 'tween deck height with no allowance for a main deck load. On this basis it was felt that the analysis should consider a main deck load of 5.25 ft. of salt water; the axial load due to this head may be defined as;

$$P_{md} = 336\left(\frac{bs}{24}\right) \tag{11}$$

The Rules define the standard 'tween deck height to be 8.5 ft.; using this value for e_i, the total axial load may

be tabulated for any number, n, of 'tween deck heights by combining equations (10) and (11) to give;

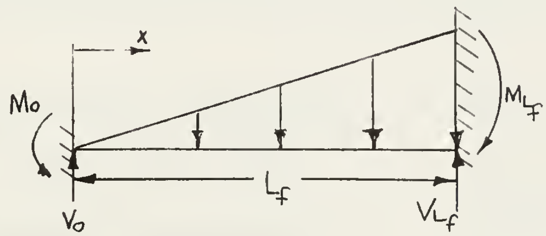
$$P = P_{t_d} + P_{m_d} = (378\ n + 336)\ \frac{bs}{24} \tag{12}$$

The bending moments due to the uniformly varying lateral load acting on the hold frame span may be defined using the results of the fixation study, $f_o = 0.5$ and $f_{L_f} = 1.0$.

Figure 3

$M_o = \frac{wL_f 2}{30}$ $\qquad$ $M_{L_f} = \frac{wL_f 2}{20}$

$V_o = \frac{3wL_f}{20}$ $\qquad$ $V_{L_f} = \frac{7wL_f}{20}$



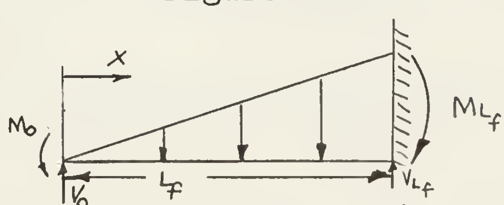
Moments and Reactions for $f_o = f_{L_f} = 1.0$

From figure 3, the end moment on the upper end of the hold frame is $(0.50)\ \frac{wL_f 2}{30} = \frac{wL_f 2}{60}$. The end moment, M_{L_f}, may be determined from the condition that the slope $(\frac{dy}{dx})$ of the elastic curve must be zero at this support for $f_{L_f} = 1.0$.

Figure 4

$M_o = \frac{wL_f^{\,2}}{60}$ $\qquad$ $M_{Lf} = \frac{7wL_f^{\,2}}{120}$

$V_o = \frac{wL_f}{8}$ $\qquad$ $V_{Lf} = \frac{3wL_f}{8}$



At $\frac{x}{L_f} = 1/2$; $\quad M = \frac{7.5\, w L_f^2}{300}$

$\frac{x}{L_f} = 7/16$; $\quad M = \frac{7.2\, w L_f^2}{300}$

Moments and Reactions for $f_o = 0.5$ and $f_{L_f} = 1.0$.

[illegible]

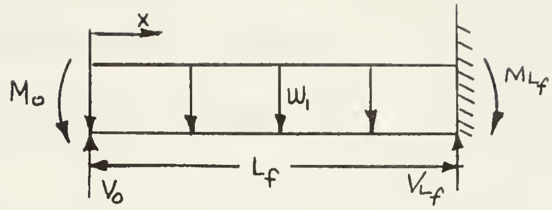
[illegible]

[illegible]

[illegible]

Figure 5

$$M_o = \frac{w_1 L_f^2}{24} \qquad M_{L_f} = \frac{5\,w_1 L_f^2}{48}$$



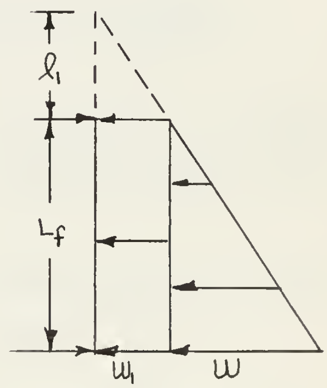
$$V_o = \frac{7\,w_1 L_f}{16} \qquad V_{L_f} = \frac{9\,w_1 L_f}{16}$$

When; $\dfrac{x}{L_f} = 7/16;$ $\qquad M = \dfrac{16.25\,w_1 L_f^2}{300}$

$\dfrac{x}{L_f} = 1/2\,;$ $\qquad M = \dfrac{15.6\,w_1 L_f^2}{300}$

Moments and Reactions for $f_o = 0.5$ and $f_{L_f} = 1.0$

When the head of salt water exceeds the height of the hold frame as shown in the sketch, the moment, M_x, can be defined by the superposition of the results of figures 4 and 5. Since $w = \rho s L_f$ and $w_1 = \rho s \ell_1$, the field moments from figures 4 and 5 will be equal when $16.25\,w_1 = 7.5\,w$ or $w_1/w = \ell_1/L_f = 0.46$. Therefore, when $0 \le \ell_1/L_f < 0.46$

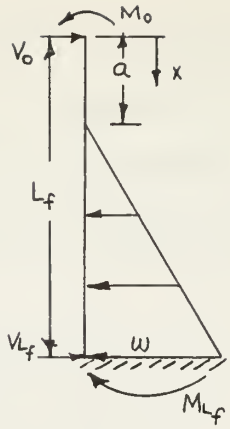


$$M = \frac{\rho s L_f^2}{300}\left[7.5 L_f + 15.6\,\ell_1\right] = \frac{s L_f^2}{4.68}\left[7.5 L_f + 15.6\,\ell_1\right] \tag{13}$$

When $\ell_1/L_f \ge 0.46$;

$$M = \frac{\rho s L_f^2}{300}\left[7.2\,L_f + 16.25\,\ell_1\right] = \frac{s L_f^2}{4.68}\left[7.2\,L_f + 16.25\,\ell_1\right] \tag{14}$$

When the head of salt water is less than the height of the hold frame as shown in the sketch, the moment relationships become more complex.



For $f_o = f_{L_f} = 1.0$; $$M_o = \frac{w}{60 L_f^2}(L_f - a)^3 (2L_f + a)$$

$$V_o = \frac{w}{20 L_f^3}(L_f - a)^3 (3L_f + a)$$

For $f_o = 0.5$ and $f_{L_f} = 1.0$; $$M_o = \frac{w}{120 L_f^2}(L_f - a)^3 (2L_f + a)$$

$$V_o = \frac{w(L_f - a)^3}{80 L_f^3}\left(10L_f + 5a - \frac{2a^5}{(L_f - a)^4}\right)$$

$$M_x = \frac{w L_f^2}{240}\left[\left(1 - \frac{a}{L_f}\right)^3 \left\{15\frac{x}{L_f}\left(2 + \frac{a}{L_f}\right) + 6\frac{a}{L_f} - 4\right\} - \left\{\frac{6\frac{x}{L_f}\left(\frac{a}{L_f}\right)^5 + 40\left(\frac{x}{L_f} - \frac{a}{L_f}\right)^3}{1 - a/L_f}\right\}\right] \quad (15)$$

Due to the complexity of equation (15), the values of field moment can be obtained for intervals of $^a/L_f$; since $w = \rho\ s(L_f - a) = \rho\ sL_f\ (1 - {}^a/L_f)$, the results can be plotted in terms of a moment coefficient, C_1.

$$M = C_1\, s\, L_f^3 \quad (16)$$

where; $$C_1 = \left(1 - \frac{a}{L_f}\right)^4 \left\{15\frac{x}{L_f}\left(2 + \frac{a}{L_f}\right) - 6\frac{a}{L_f} - 4\right\} - 6\frac{x}{L_f}\left(\frac{a}{L_f}\right)^5 - 40\left(\frac{x}{L_f} - \frac{a}{L_f}\right)^3$$

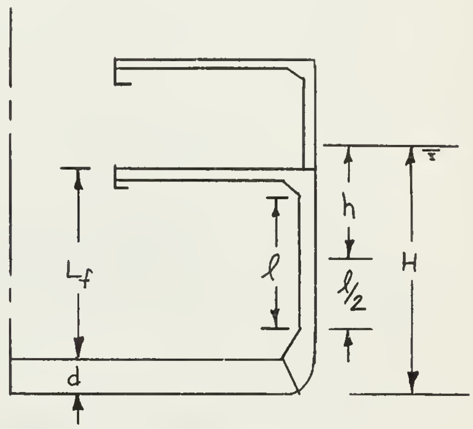
The variation of C_1 with $^a/L_f$ is plotted as the solid line in Figure VII.

Other Methods of Describing the Lateral Loading

During the period of analysis, other methods were considered for describing the lateral loading on the hold

frame; some of these methods are reasonable approximations for initial design calculations and are therefore included. On the other hand, some of the methods investigated proved to be unfruitful or unrealistic; these are mentioned only for completeness.

1. Approximation used by the ABS Rules.



In section 8 of the Rules, the lateral load is defined in terms of the head, h, acting at the midpoint of the unsupported span. References (7) and (8) indicate that on the span length, L_f, when $h \geq L_f/2$, the actual uniformly varying load may be approximated by a uniformly distributed load, $w_1 = \rho sh$. Using the results shown in figure 4 and 5 for $h = L_f/2$ or $w_1 = w/2$; the two variations of moment are shown in figure 6.

<u>Actual</u>

$$M_x = \frac{w L_f^2}{300}\left[37.5\left(\frac{x}{L_f}\right) - 5 - 50\left(\frac{x}{L_f}\right)^3\right]$$

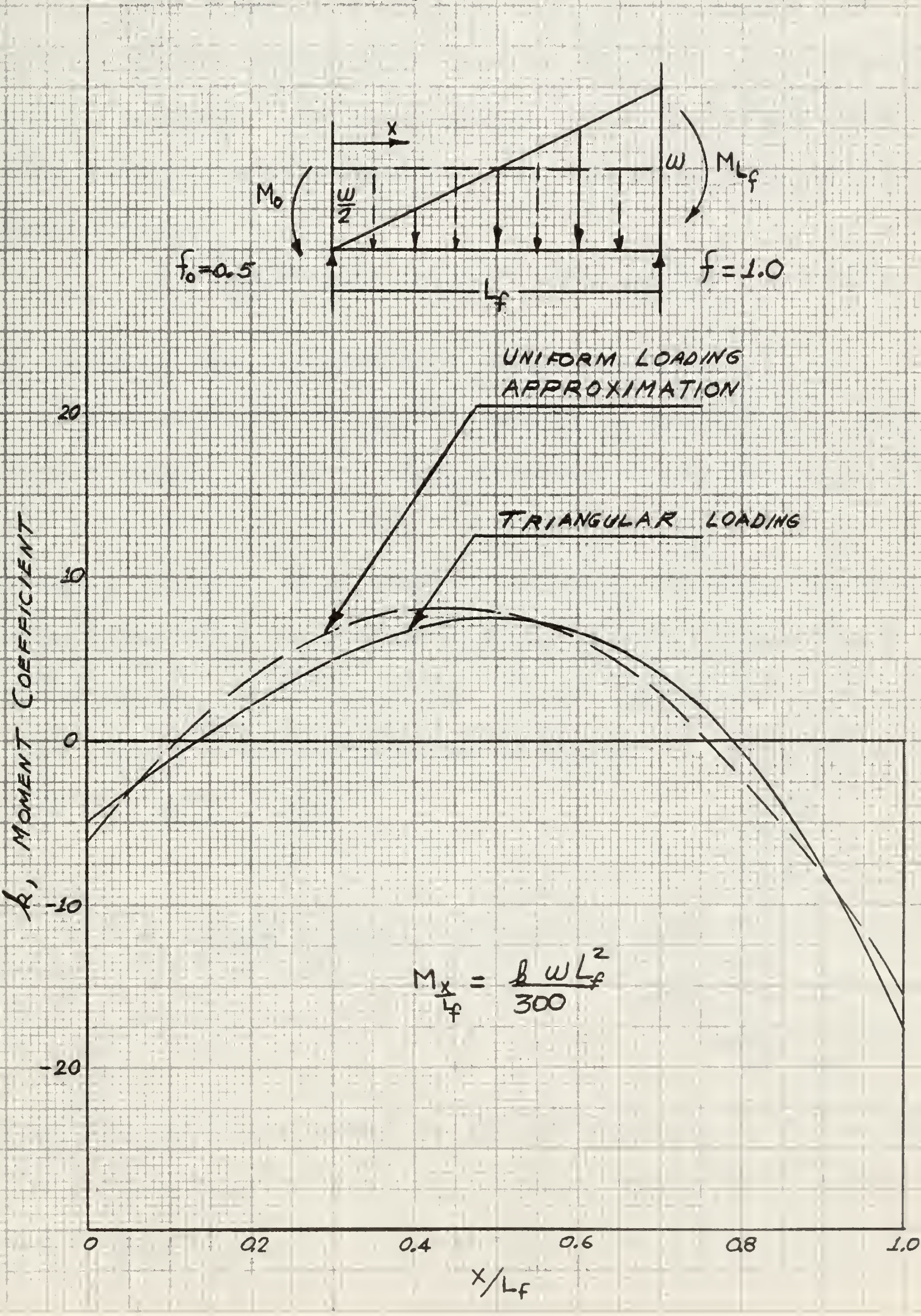
<u>Approximate</u>

$$M_x = \frac{w L_f^2}{300}\left[65.6\left(\frac{x}{L_f}\right) - 6.25 - 75\left(\frac{x}{L_f}\right)^2\right]$$

For the load relationships illustrated in figure 6, the distribution of moment for the uniformly distributed load is a reasonable approximation to the actual distribution due to the uniformly varying load. The design of the hold frame or any vertical member subjected to a

Figure 6

Variation of Bending Moment for Triangular Loading and the Approximation by a Uniformly Distributed Loading.



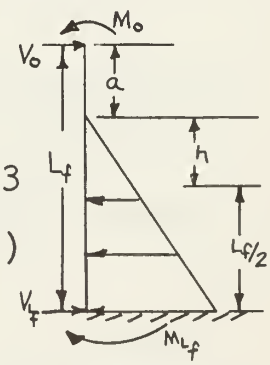
lateral loading due to water pressure could be based upon such an approximation when the scantlings are based upon the field moment. As the head increases above the top of the hold frame, the uniform load approximation will define field moments which tend to approach those from the actual loading. The calculations for the uniform load approximation are included in the analysis; the field moment being;

$$M = \frac{16.25}{300}(64)\, shL_f^2 = 3.465\ sh\ L_f^2 \qquad (17)$$

2. Study of ABS Limitation on Approximation.

The uniform load approximation as described in method 1 is subjected to the limitation in the Rules that $h \geq .4\ell$, ie. if $h < .4\ell$, the field moment shall be defined for a head, $h = .4\ell$. This becomes necessary because the head at midspan does not define a field moment which is as large as the field moment due to the triangular loading. This can be illustrated by manipulation of equation (17) with $h = L_f\left(\frac{1}{2} - \frac{a}{L_f}\right)$;

$$M = 3.465\ sL_f^3\left(\tfrac{1}{2} - a/L_f\right) = C_1\ sL_f^3 \qquad (18)$$



Equation (18) is plotted as the broken line in Figure VII. The intersection of the two curves illustrates that with end fixations of $f_o = 0.5$ and $f_{L_f} = 1.0$ the uniform load

approximation is only feasible for $a/L_f \leq 0.05$.

The derivation of the above limitation of $a/L_f \leq 0.05$ prompted some study of other possible end fixations which might give the value of $a/\ell = 0.10$ which is prescribed in the Rules. The ABS, unlike some Classification Societies, does not prescribe the sizes of beam knees and hold frame brackets to be associated with particular hold frame scantlings; therefore, this study of end fixation was conducted using the unsupported span length.

The definition of appropriate end fixations for the unsupported span is somewhat nebulous; however, the following combinations were used and equations (16) and (18) were modified appropriately for each combination;

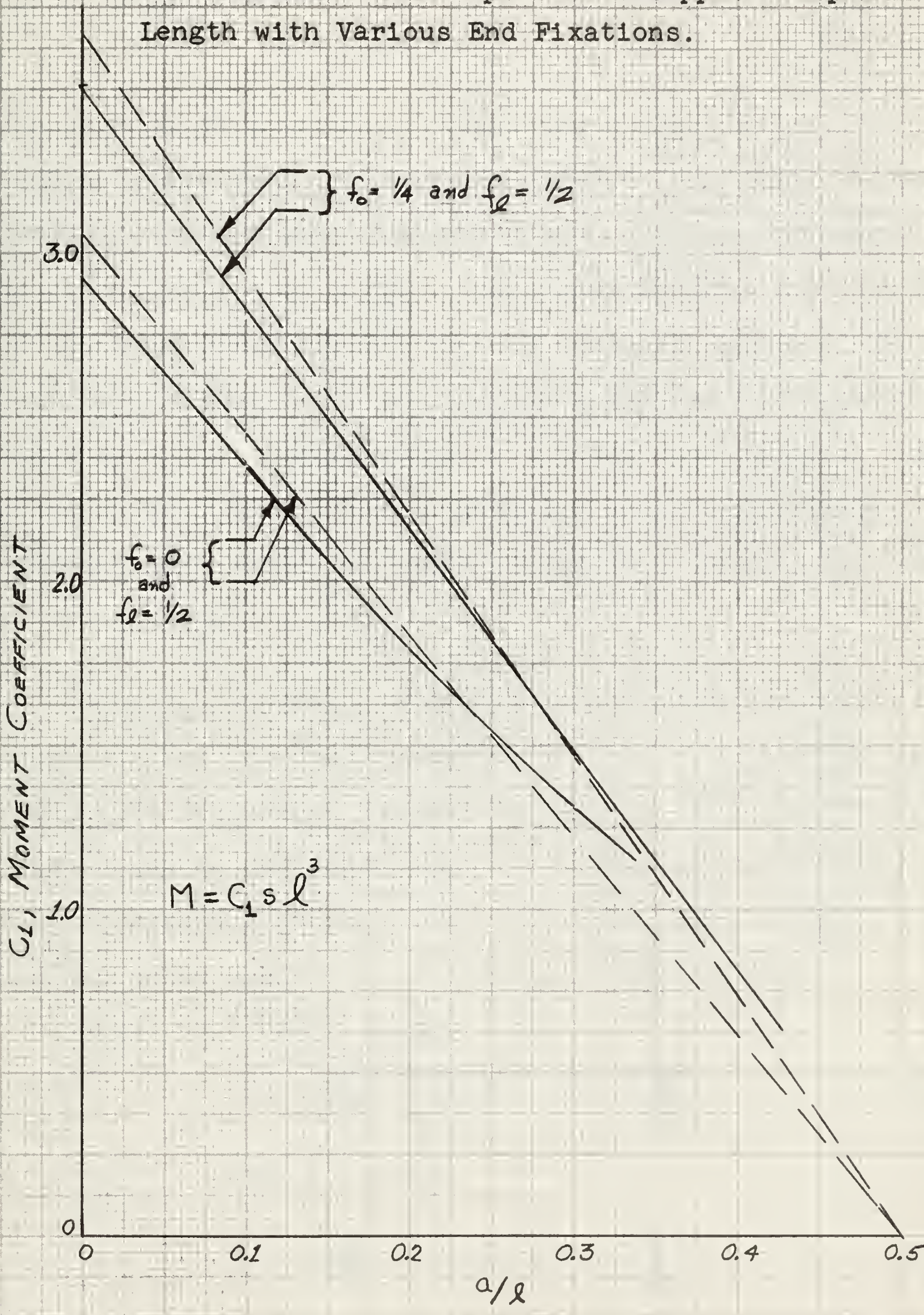
f_o	f
0	$\frac{1}{2}$
$\frac{1}{4}$	$\frac{1}{2}$
0	3/4
0	1.0

The results for the first two combinations are plotted in figure 7; the limiting values of a/ℓ for the latter two combinations gave even greater variation from the desired value of 0.10.

The first combination of fixations, $f_o = 0$ and $f = 0.50$, produced some results which indicated that it should be included in the calculations. First, the fixations most nearly satisfied the uniform load limitation of the Rules, ie. $a/\ell \cong 0.10$. Secondly, the

Figure 7

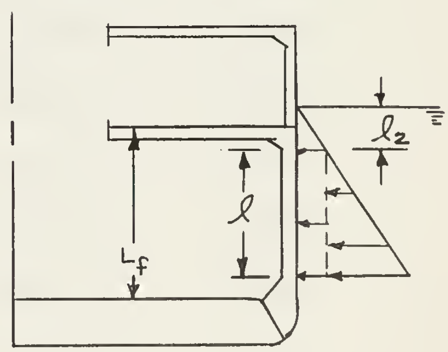
Field Moments Based Upon the Unsupported Span Length with Various End Fixations.



field moment expressed in terms of the uniform load approximation is;

$$M = 6.13\ sh\ell^2 \tag{19}$$

Previous to this fixation study, one of the design assumptions was that the relation between the overall hold frame length and the unsupported span could be expressed as; $\ell = 3/4L_f = L_f - \frac{2L_f}{8}$. This assumes that the length of the hold frame bracket and the combined length of the beam knee and depth of the deck beam may each be approximated by $L_f/8$. Substituting $\ell = 3/4L_f$ into equation (19) gives a field moment $M = 3.45\ sh\ L_f^2$ which approximates equation (17) which was based on the full length, L_f, and $f_o = 0.5$ and $f_{L_f} = 1.0$.



With $f_o = 0$ and $f_\ell = 0.50$, equations for the field moment based upon the actual lateral loading may be developed, as were equations (13) and (14), and expressed as;

When $0 \leq \ell_2/\ell < 0.478$:

$$M = \frac{s\ell^2}{1.875}\left[5.5\ell + 11.18\ell_2\right] \tag{20}$$

When $\ell_2/\ell \geq 0.478$;

$$M = \frac{s\ell^2}{1.875}\left[5.32\ell + 11.5\ell_2\right] \tag{21}$$

APPENDIX C - SECTION CHARCTERISTICS

Section Scantlings

The series of welded inverted angles listed in Table 6 of the Rules will be used for the hold frame members in the design calculations. The following is a tabulation of section scantlings; also included is the average value of ℓ^2 (NF) for the respective sections.

Section No.	Section Scantlings	ave. ℓ^2 (NF)
1	6 x 2.50 x .313 x .375	1500
2	6 x 2.94 x .313 x .475	1895
3	6 x 3.50 x .340 x .385	1960
4	7 x 3.00 x .375 x .475	2560
5	8 x 2.98 x .350 x .500	3300
6	8 x 3.03 x .400 x .500	3845
7	8 x 3.45 x .375 x .525	4030
8	8 x 3.50 x .425 x .525	4250
9	9 x 3.45 x .400 x .550	4940
10	10 x 3.40 x .375 x .575	5740
11	10 x 3.50 x .475 x .575	6380
12	10 x 3.95 x .425 x .575	7125
13	12 x 3.45 x .450 x .600	8280
14	13 x 4.00 x .375 x .610	10050
15	15 x 3.52 x .520 x .650	13600
16	18 x 3.95 x .450 x .625	18530
17	18 x 4.00 x .500 x .625	

[illegible]

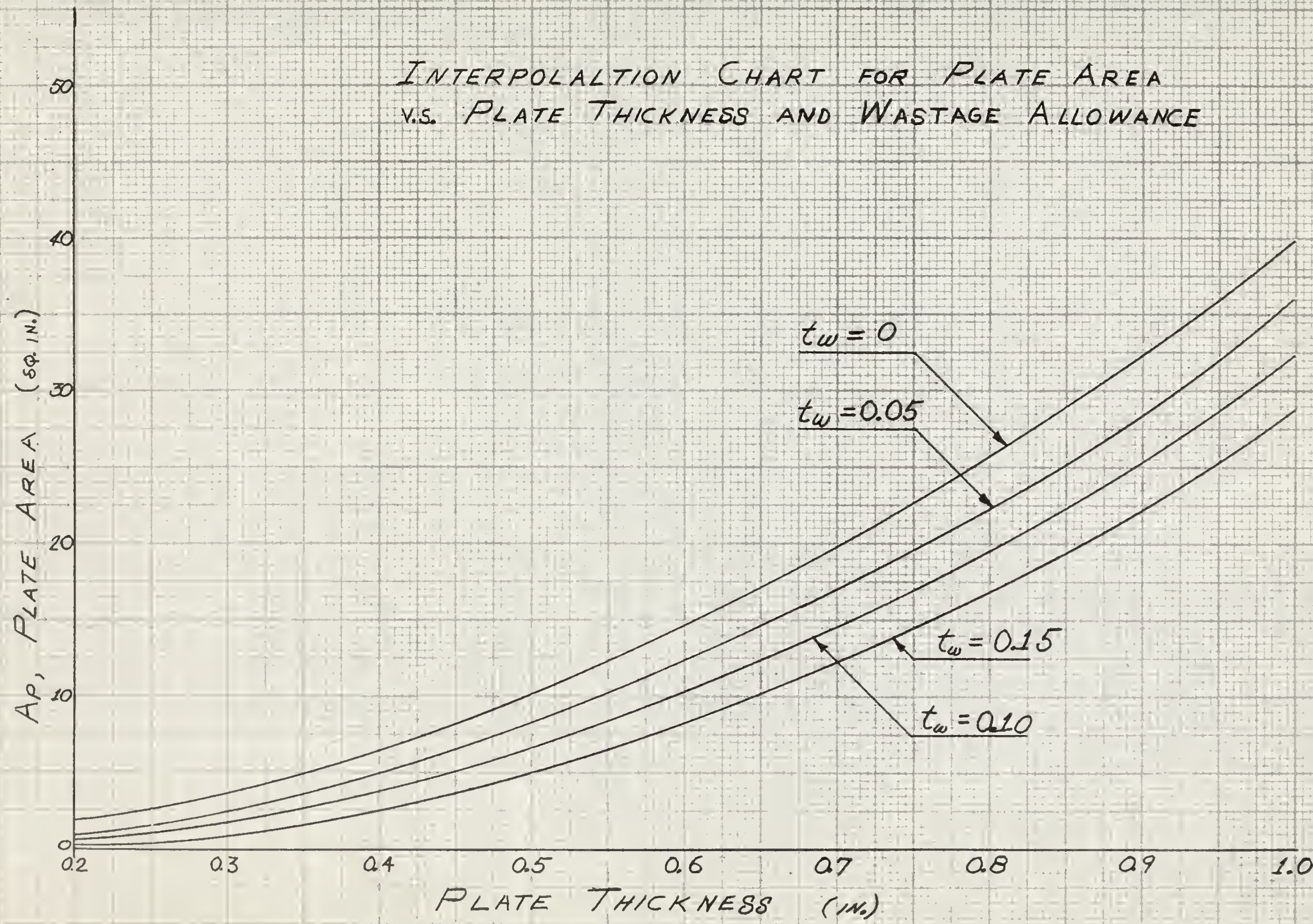
Section Areas

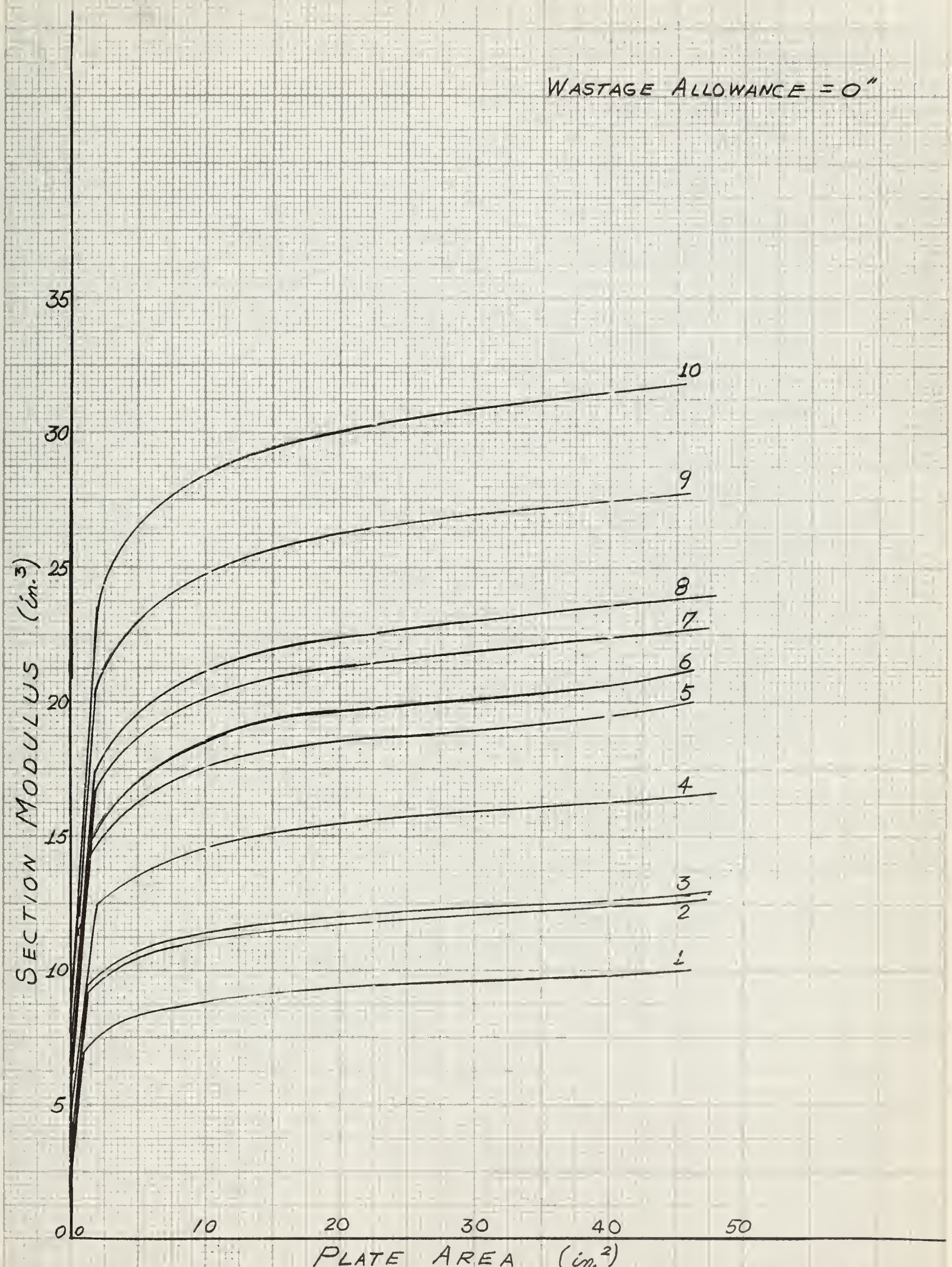
The section area for each welded inverted angle is tabulated below as a function of wastage allowance; the areas were obtained from available data presented in reference (6).

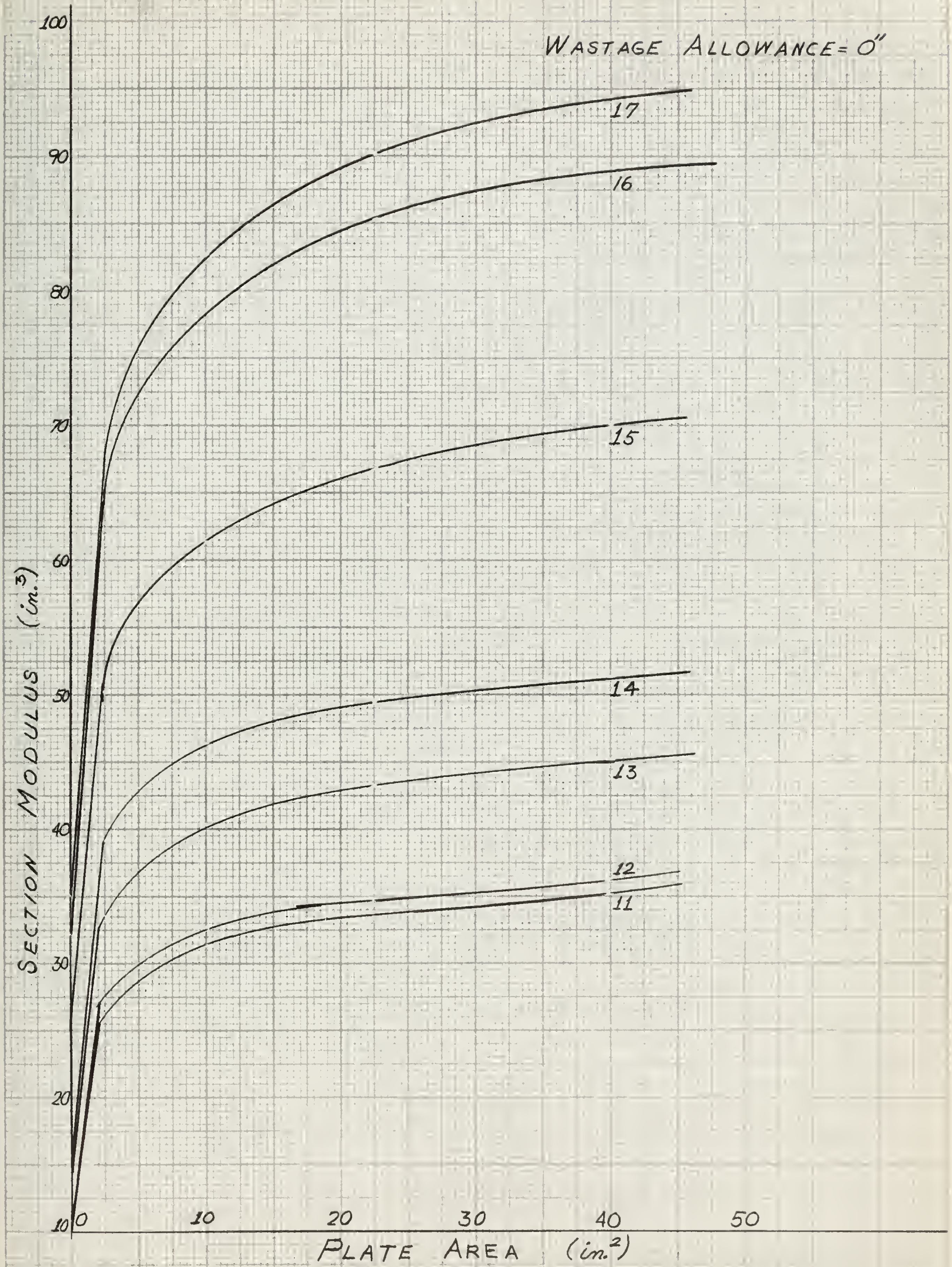
Section No.	$t_w = 0$	$t_w = 0.05$	$t_w = 0.10$	$t_w = 0.15$
1	2.70	2.28	1.87	1.46
2	3.13	2.69	2.26	1.83
3	3.26	2.80	2.34	1.88
4	3.87	3.39	2.91	2.43
5	4.12	3.58	3.04	2.51
6	4.52	4.12	3.45	2.92
7	4.61	4.06	3.45	2.95
8	5.02	4.46	3.84	3.35
9	5.28	4.68	4.07	3.47
10	5.49	4.84	4.19	3.54
11	6.49	5.84	5.19	4.54
12	6.28	5.59	4.91	4.23
13	7.20	6.45	5.70	4.95
14	7.09	6.26	5.42	4.59
15	9.75	8.85	7.95	7.05
16	10.29	9.21	8.14	7.06
17	11.19	10.10	9.02	7.94

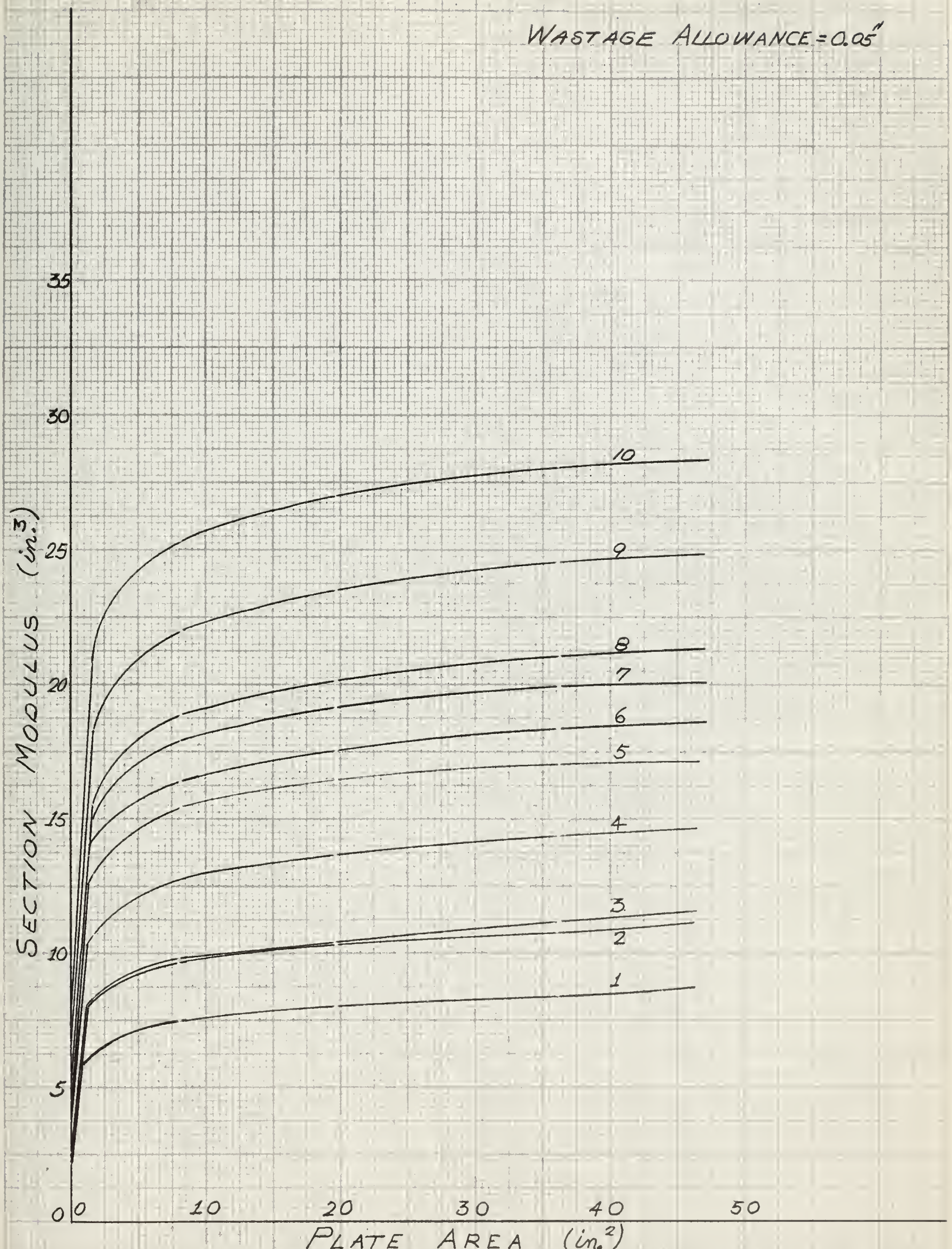
Section Modulus Graphs

The following section modulus graphs were made available to the author by The Department of Naval Architecture at the Massachusetts Institute of Technology. The section moduli are based upon an effective breadth of 40t, or more accurately as $40\ (t - t_w)$ with the inclusion of a wastage allowance. The section moduli are plotted versus plate area, A_p, where $A_p = 40\ (t - t_w)^2$. The first plot gives the plate area for any plate thickness up to one inch for wastage allowances of 0, 0.05, 0.10, and 0.15 inches.

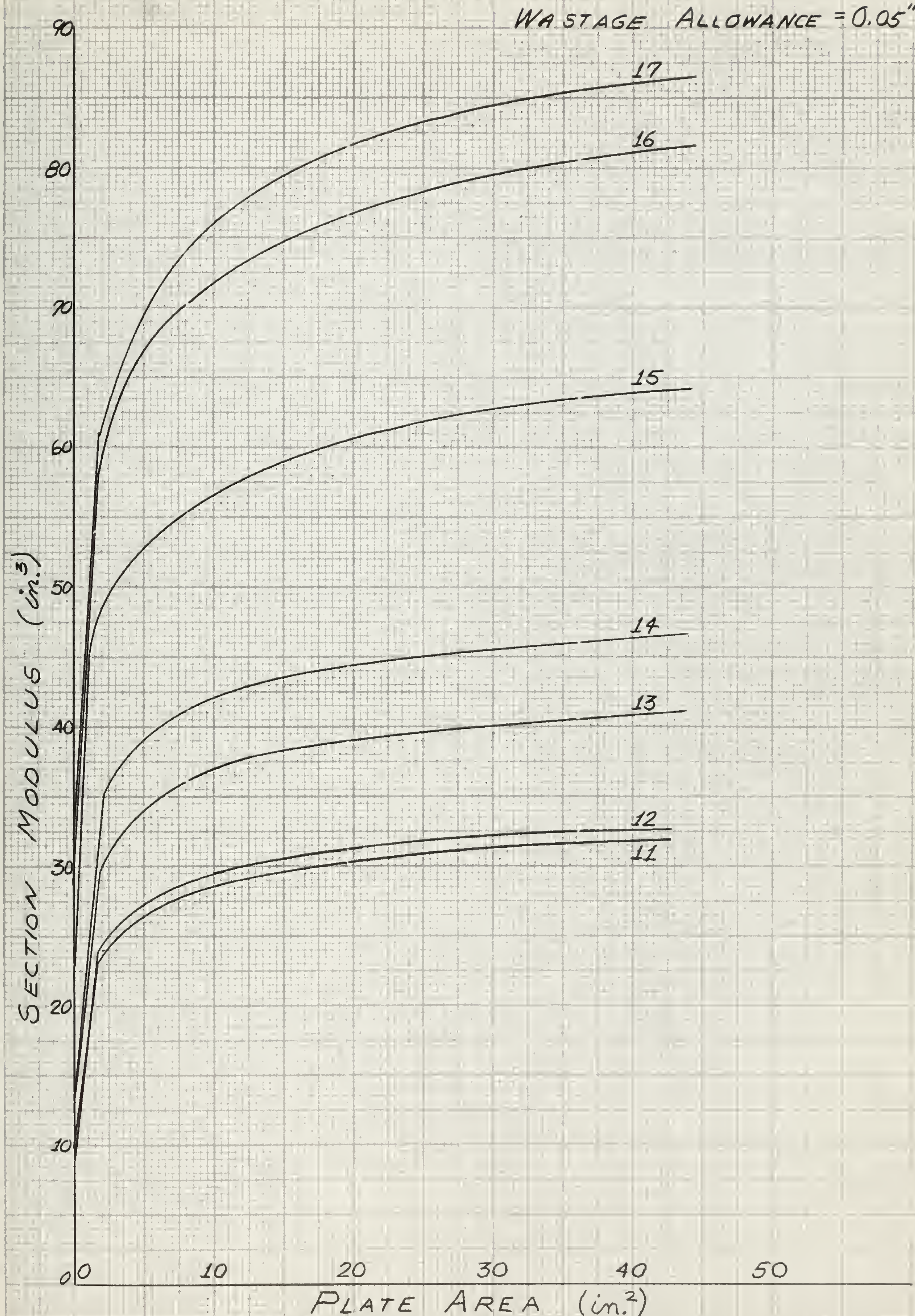

INTERPOLALTION CHART FOR PLATE AREA
V.S. PLATE THICKNESS AND WASTAGE ALLOWANCE
$t_w = 0$
$t_w = 0.05$
$t_w = 0.15$
$t_w = 0.10$
AP, PLATE AREA (SQ. IN.)
0
10
20
30
40
50
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
PLATE THICKNESS (IN.)


WASTAGE ALLOWANCE = 0"
SECTION MODULUS (in.^{3})
PLATE AREA (in.^{2})
0
5
10
15
20
25
30
35
0
10
20
30
40
50
1
2
3
4
5
6
7
8
9
10

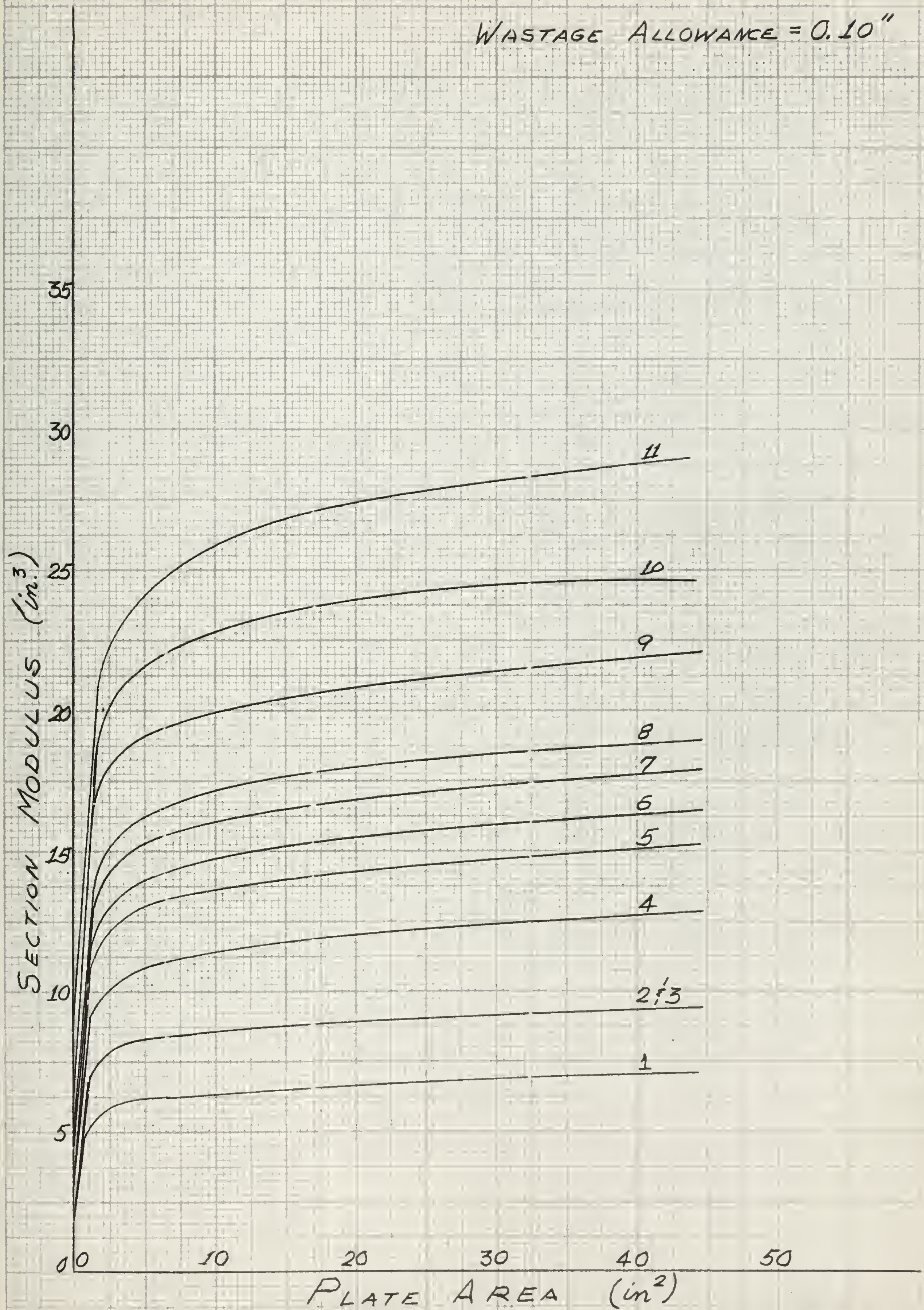

WASTAGE ALLOWANCE = 0"
17
16
15
14
13
12
11
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
SECTION MODULUS (in.³)
PLATE AREA (in.²)



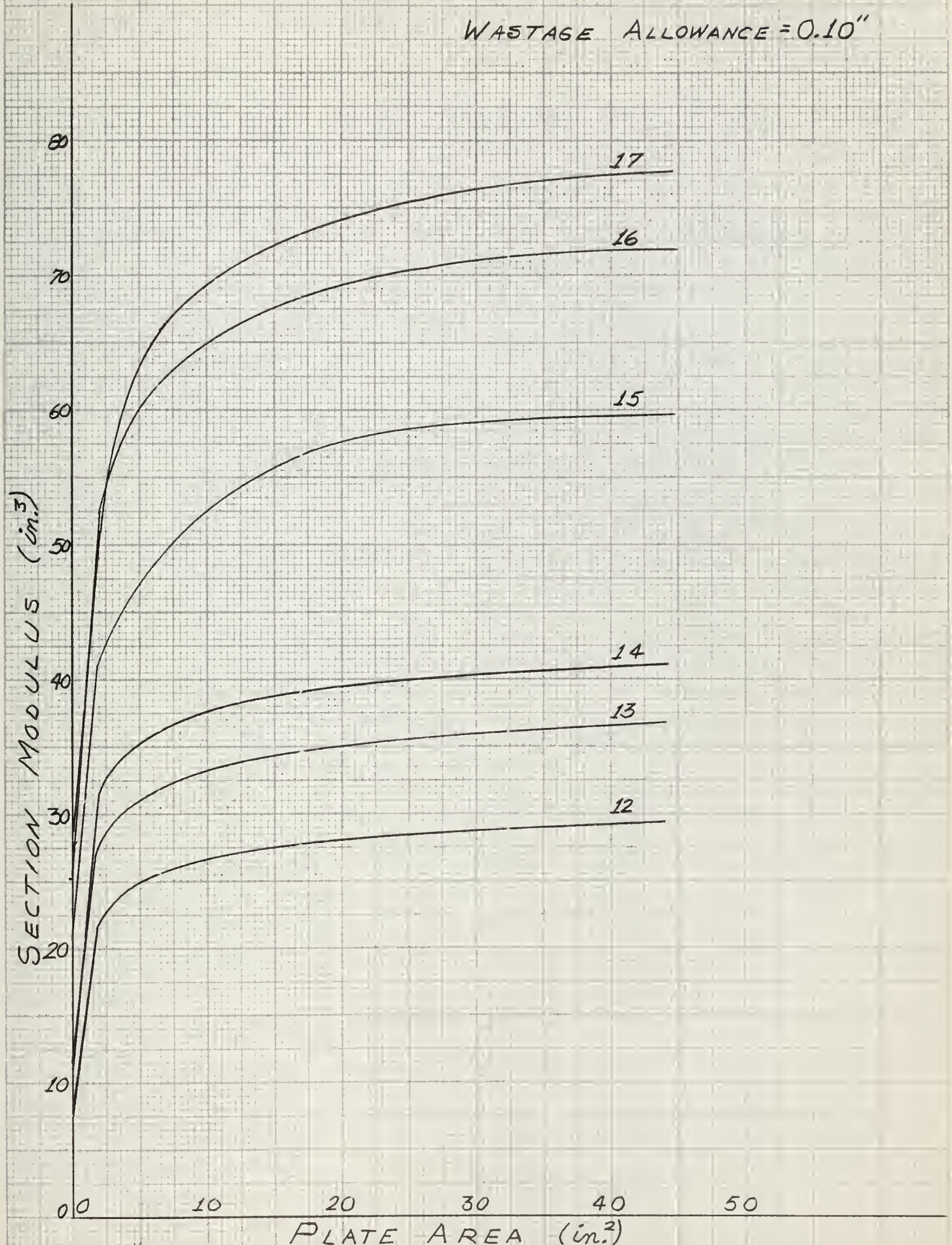
WASTAGE ALLOWANCE = 0.05"
SECTION MODULUS (in.^{3})
PLATE AREA (in.^{2})
0
5
10
15
20
25
30
35
0
10
20
30
40
50
1
2
3
4
5
6
7
8
9
10

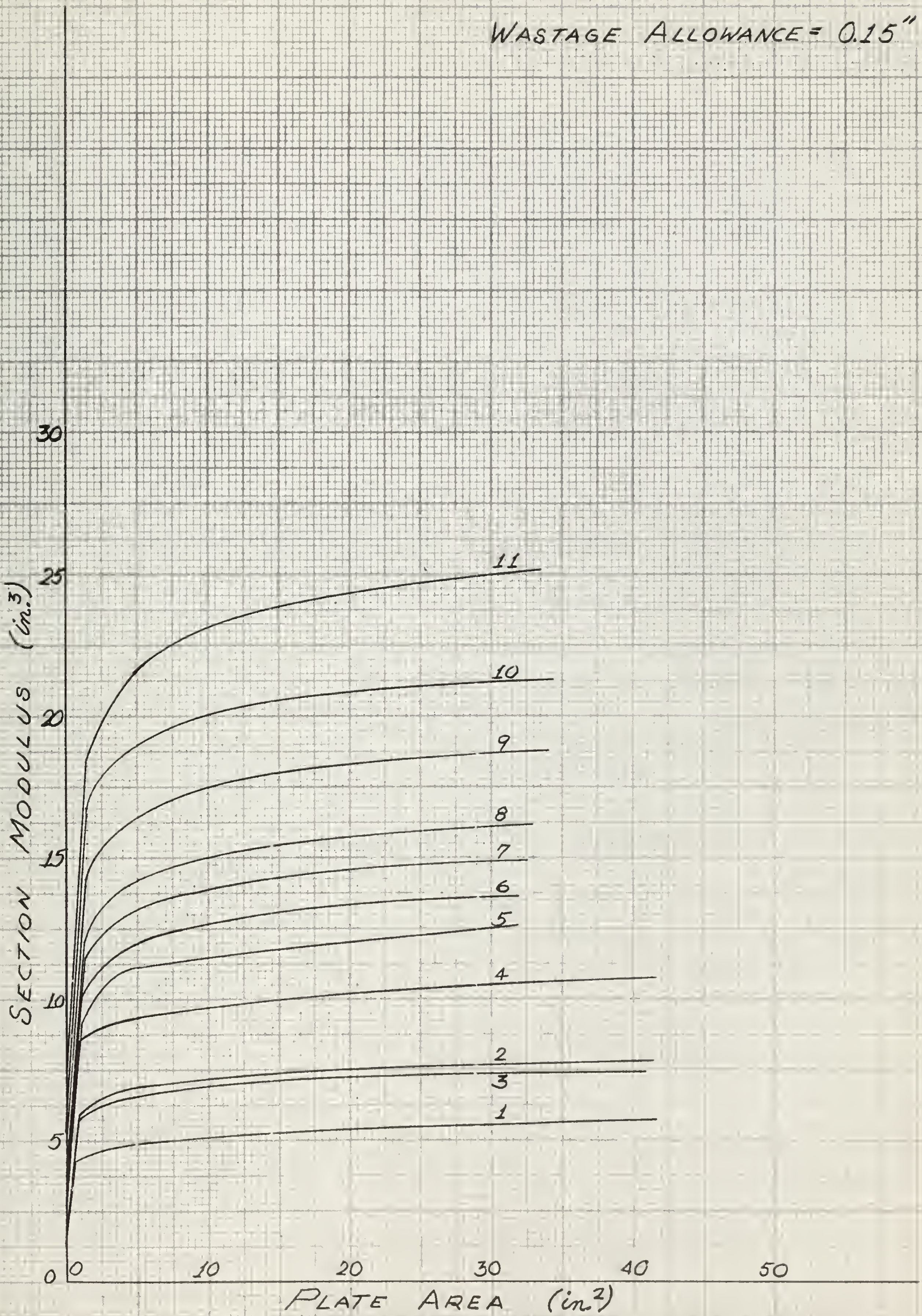


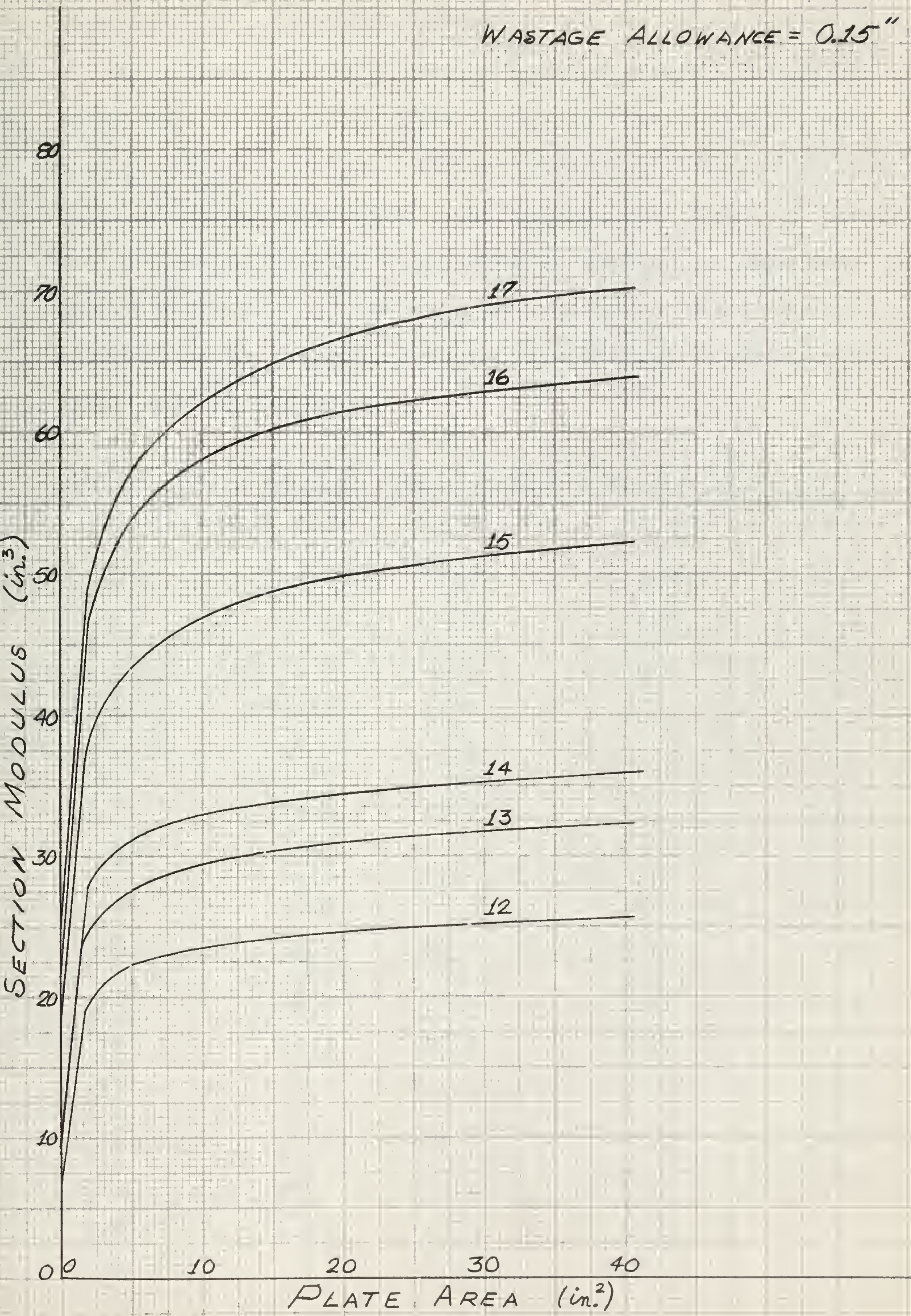
WASTAGE ALLOWANCE = 0.05"
17
16
15
14
13
12
11
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
SECTION MODULUS (in.³)
PLATE AREA (in.²)



WASTAGE ALLOWANCE = 0.10"
SECTION MODULUS (in.³)
PLATE AREA (in²)
0
5
10
15
20
25
30
35
0
10
20
30
40
50
11
10
9
8
7
6
5
4
2 & 3
1


WASTAGE ALLOWANCE = 0.10"
SECTION MODULUS (in.³)
PLATE AREA (in.²)
0
10
20
30
40
50
60
70
80
0
10
20
30
40
50
17
16
15
14
13
12


WASTAGE ALLOWANCE = 0.15"
SECTION MODULUS (in.³)
PLATE AREA (in.²)
0
5
10
15
20
25
30
0
10
20
30
40
50
1
2
3
4
5
6
7
8
9
10
11


WASTAGE ALLOWANCE = 0.15"
17
16
15
14
13
12
SECTION MODULUS (in.^{3})
0
10
20
30
40
50
60
70
80
0
10
20
30
40
PLATE AREA (in.^{2})

Section Moduli For Balanced Design

From the preceeding section modulus graphs, it can be noted that as the plate area increases (increasing t), the section modulus changes from an increasing linear variation to a non-linear variation. The intersection point of these two variations defines a symmetrical section or balanced design where $A_f = A_p$ and thus the neutral axis is at the midpoint of the distance between the extreme fibers of the plate and the flange.

Section No.	$t_w = 0$	$t_w = 0.05$	$t_w = 0.10$	$t_w = 0.15$
1	6.8	5.8	4.8	3.9
2	8.8	8.0	7.0	6.0
3	9.2	7.9	6.8	5.7
4	11.7	10.3	9.1	8.5
5	14.2	12.6	10.8	9.2
6	14.8	14.1	11.6	10.0
7	16.8	15.0	13.1	11.5
8	17.4	15.5	13.6	12.1
9	20.4	18.3	16.3	14.3
10	23.6	21.1	18.8	16.5
11	25.5	23.0	20.7	18.3
12	27.2	24.6	21.7	19.1
13	32.7	29.5	26.6	23.5
14	39.2	35.3	31.6	27.8
15	49.7	45.2	41.1	36.8
16	64.5	58.3	52.4	46.5
17	67.4	61.1	55.1	48.6

Section Area For Balanced Design

The section area for balanced design is the sum of the area of the inverted angle plus the respective plate area, $A_p = 40\ (t - t_w)^2$, corresponding to the "knuckle" point on the section modulus curves. The areas were obtained from available data presented in reference (6).

Section No.	$t_w = 0$	$t_w = 0.05$	$t_w = 0.10$	$t_w = 0.15$
1	3.64	3.08	2.53	1.99
2	4.52	3.92	3.33	2.74
3	4.61	3.96	3.31	2.67
4	5.30	4.65	4.00	3.35
5	5.61	4.90	4.19	3.50
6	6.03	5.59	4.62	3.93
7	6.43	5.68	4.88	4.19
8	6.85	6.10	5.29	4.61
9	7.18	6.38	5.58	4.79
10	7.45	6.60	5.76	4.92
11	8.50	7.65	6.80	5.96
12	8.55	7.64	6.74	5.84
13	9.27	8.32	7.38	6.44
14	9.53	8.47	7.41	6.36
15	12.04	10.93	9.83	8.74
16	12.76	11.46	10.16	8.87
17	13.69	12.37	11.07	9.77

APPENDIX D - SAMPLE CALCULATIONS

The following sample calculations illustrate the hold frame design procedure as well as the approximate procedures for a 600 ft. ship of intermediate depth.

Step 1: from Table 12 in the Rules,

$D_s = \frac{7L}{100} + 7 = 49$ ft. $\qquad s = 32.0$ in.

$B = 2\,D_s = 98$ ft. $\qquad t_s = 0.755$ in.

$d = (\frac{L}{20} + 18)\,\frac{1}{12} = 4.0$ ft. $\qquad H = 30$ ft.

Step 2: assume three 'tween deck heights, $n = 3$.

$L_f = D_s - d - 8.5n = 19.5$ ft. $\qquad \ell = 3/4\ L_f = 14.6$ ft.

$h = H - d - L_f/2 = 16.25$ ft. $\qquad b = 1/2(B - L/20) = 34$ ft.
therefore, use $b = 30$ ft.

Step 3: since the available freeboard is $D_s - H = 19$ ft., assume the bulkhead deck is one deck below the strength deck and $h_1 = (3)(8.5) = 25.5$ ft.

$$NF = \frac{32}{12}\left[16.25 + \frac{(30)25.5}{100}\right] = 63.7$$

For $NF = 63.7$ and $\ell = 14.6$, Table 6 in the Rules gives the following possible combinations and the required sections for each.

ℓ	NF	Section Required	Section Selected
14	65	13 x 4.00	15 x 3.52
15	60	15 x 3.52	
15	65	15 x 3.52	

When the combination of NF and ℓ from the calculations may be satisfied by more than one structural section, the larger section shall be selected for further analysis.

Step 4: the area of the plate, section area, and the section modulus for section no. 15, (15 x 3.52), may be determined from the graphs and tabulations of Appendix C for each wastage allowance.

$A_p = 40(t_s - t_s)^2$ for $t_s = 0.755$ in.

Quantity	$t_w = 0$	$t_w = 0.05$	$t_w = 0.10$	$t_w = 0.15$
$A_f + A_w$	9.75	8.85	7.95	7.05
Ap	22.8	19.8	17.2	15.6
A	32.55	28.65	25.15	22.65
Z	67.7	61.7	55.3	49.5

Ap = Af for balanced design

Quantity	$t_w = 0$	$t_w = 0.05$	$t_w = 0.10$	$t_w = 0.15$
A	12.04	10.93	9.83	8.74
Z	49.7	45.2	41.1	36.8

Step 5: equation (12) for the axial load

$$P = \left[378(3) + 336 \right] \frac{(30)(32)}{24} = 58{,}800 \text{ lb.}$$

The field moment is determined from the various equations for the full load draft and for the superposition of a L/20 wave height.

H = 30 ft.

$\ell_1 = H - L_f - d = 6.5$ ft.

$\ell_1 / L_f = \frac{6.5}{19.5} < 0.46$

Eqn. (13)

$$M = \frac{(32)(19.5)^2}{4.68}\left[7.5(19.5) + 15.6(6.5)\right]$$

M = 652,000 in - lb

Stresses for $A_p = 40(t_s - t_w)^2$

t_w	0	0.05	0.10	0.15
P/A	1820	2060	2350	2600
M/Z	9620	10560	11780	13150
σ_T	11440	12620	14130	15750

Stresses for $A_p = A_f$

t_w	0	0.05	0.10	0.15
P/A	4900	5400	6000	6750
M/Z	12900	14200	15600	17500
σ_T	17800	19600	21600	24250

Eqn. (17) h = 16.25 ft.

$M = 3.465\ (32)(16.25)(19.5)^2$

M = 684,000 in - lb

Eqn. (21) $\ell_2 = 6.5 + \frac{L_f}{8} = 8.9$ ft.

$\ell_2/\ell = \frac{8.9}{14.6} > 0.478$

$$M = \frac{(32)(14.6)^2}{1.875}\left[5.32(14.6) + 11.5(8.9)\right]$$

M = 654,000 in - lb

H + L/40 = 45 ft.

$\ell_1 = 6.5 + 15 = 21.5$ ft.

$\ell_1 / L_f > 0.46$

Eqn. (14)

$$M = \frac{(32)(19.5)^2}{4.68}\left[7.2(19.5) + 16.25(21.5)\right]$$

$M = 1.25 \times 10^6$ in - lb

t_w	0	0.05	0.10	0.15
P/A	1820	2060	2350	2600
M/Z	19050	20900	23300	26000
σ_T	20870	22960	25650	28600

t_w	0	0.05	0.10	0.15
P/A	4900	5400	6000	6750
M/Z	24700	27200	29900	33500
σ_T	29600	32600	35900	40250

Eqn. (17) h = 16.25 + 15 = 31.25 ft.

$M = 3.465\ (32)(31.25)(19.5)^2$

$M = 1.315 \times 10^6$ in - lb

Eqn. (21) $\ell_2 = 8.9 + 15 = 23.9$ ft.

$$M = \frac{(32)(14.6)^2}{1.875}\left[5.32(14.6) + 11.5(23.9)\right]$$

$M = 1.37 \times 10^6$ in - lb

The bending stresses for the field moment from equations (17) and (21) may be obtained by simply using the ratio of moments to increase the bending stresses defined by equations (13) and (14).

The tabulation of original data in Appendix E includes only the bending stresses defined by equation (13) or (14) and equation (17).

Step 6: to determine allowable σ_p for head of 45 ft. and t_w = 0.10 in., the following data is used.

P/A = 2350 psi	A_p = 17.2 sq. in.
M/Z = 23300 psi	A = 25.15 sq. in.
ℓ = 14.6 ft.	

For Ap = 17.2 sq. in., the moment of inertia for section no. 15 is found to be 675 in.^{4}.

$$\text{slenderness ratio, } \ell/r = \frac{(12)(14.6)}{\sqrt{675/25.15}} = 33.8$$

$$\text{allowable } \sigma_p = \frac{P/A}{1 - \frac{M/Z}{27{,}000}} = \frac{2350}{1 - \frac{23{,}300}{27{,}000}} = 17{,}100 \text{ psi}$$

APPENDIX E - ORIGINAL DATA

1. Tabulation of total stresses defined by the uniformly varying load distribution. Abbreviation codes are:

t_s - $A_p = 40\,(t_s - t_w)^2$

b_d - $A_p = A_f$ for balanced design

H - full load draft

HL - full load draft plus L/20 wave height

					t_w, Wastage Allowance			
L	Ds	n	Ap	head	0	0.05	0.10	0.15
300	22	1	t_s	H	9170	10960	13400	17270
			t_s	HL	17740	21160	25900	33170
			b_d	H	13450	15730	19280	24200
			b_d	HL	23500	27430	33680	42100
300	28	1	t_s	H	9770	11080	12780	15350
			t_s	HL	19120	21680	24980	29720
			b_d	H	13130	14920	17050	18680
300	38	2	t_s	H	8520	9630	12320	15750
			t_s	HL	22270	25260	30620	38300
			b_d	H	13470	15350	17930	21300
400	28	1	t_s	H	9260	10410	11650	13900
			t_s	HL	17210	19360	21550	25700
			b_d	H	12400	13960	15680	18000
			b_d	HL	22300	24960	27980	32100
400	35	2	t_s	H	10830	12280	14280	16830
			t_s	HL	20810	23480	27180	31830
			b_d	H	15570	17500	20180	23100
400	47.5	3	t_s	H	10960	12750	15920	18100
			t_s	HL	20860	23900	27650	33150
			b_d	H	16770	18750	21700	24950
			b_d	HL	28620	31950	36900	42050
500	36	2	t_s	H	11890	13190	14740	16450
			t_s	HL	17860	19830	22040	24700
			b_d	H	16770	18390	20310	22610
			b_d	HL	24620	27090	29810	33110

500	36	3	ts	H	12130	13570	15540	27600
			ts	HL	19490	21970	25140	28500
			bd	H	17980	19970	22620	25830
			bd	HL	27480	30470	34520	39380
500	42	2	ts	H	11260	12650	14520	16780
			ts	HL	22980	25750	29420	34180
			bd	H	15970	17790	20060	22950
500	42	3	ts	H	10580	12000	13850	16070
			ts	HL	17730	20040	23050	26620
			bd	H	17360	19470	22100	25400
500	58	3	ts	H	8670	9740	11060	12690
			ts	HL	18120	20210	22790	25910
			bd	H	12450	13700	15120	16930
			bd	HL	24400	26950	29720	33200
500	58	4	ts	H	10360	11760	13620	15850
			ts	HL	20360	22840	26270	30300
			bd	H	16550	18350	20500	23270
			bd	HL	29100	32200	35900	40600
600	48	3	ts	H	12750	14190	16130	18620
			ts	HL	23220	25840	29470	33890
			bd	H	19830	22100	24950	28550
			bd	HL	33080	36950	41350	47250
600	49	3	ts	H	11440	12620	14130	15750
			ts	HL	20870	22960	25650	28600
			bd	H	17800	19600	21600	24250
600	66	4	ts	H	11260	12590	14170	15790
			ts	HL	22710	25310	28410	31690
			bd	H	17420	19110	21120	23660
			bd	HL	32650	35760	39420	44060
600	66	5	ts	H	9910	11330	12890	14560
			ts	HL	17760	20120	22690	25910
			bd	H	17920	19900	22300	25370
			bd	HL	28300	31100	34850	39600
700	56	3	ts	H	11330	12600	14140	16240
			ts	HL	25400	28400	31640	36440
			bd	H	18070	20030	22400	25520
			bd	HL	37170	41130	45950	51820
700	56	4	ts	H	11980	13460	15600	17590
			ts	HL	23180	26060	30300	34040
			bd	H	20860	23300	26260	30200

700	56	4	ts	H	10660	11730	13020	15490
			ts	HL	20340	22180	24670	29540
			bd	H	18400	20230	22300	25000
700	78	5	ts	H	9630	10830	12220	14100
			ts	HL	21680	24250	27270	31350
			bd	H	16360	18150	20310	23300
			bd	HL	32240	35800	——	——
700	78	6	ts	H	9990	11270	12830	15070
			ts	HL	20340	22820	25760	30270
			bd	H	19620	21970	24850	28650
			bd	HL	32600	36400	——	——

2. Tabulation of total stresses defined by the uniform load approximation. (Abbreviation codes are the same as in 1.)

					t_w, Wastage Allowance			
L	Ds	n	Ap	head	0	0.05	0.10	0.15
300	22	1	ts	H	9840	11760	14400	18470
			ts	HL	18540	22160	27100	34670
			bd	H	14300	16760	20480	25700
			bd	HL	24500	28630	35080	43900
300	28	1	ts	H	9770	11080	12780	15350
			ts	HL	20370	23130	26580	31700
			bd	H	13130	14920	17050	18680
300	38	2	ts	H	10500	11860	14940	18980
			ts	HL	23470	26560	32220	40200
			bd	H	15820	18010	21050	24950
400	28	1	ts	H	12160	13660	15750	18300
			ts	HL	20310	22760	26150	30400
			bd	H	16000	17960	20180	23100
			bd	HL	26100	29160	32680	37500
400	35	2	ts	H	11460	12980	15130	17830
			ts	HL	21610	24380	28280	33130
			bd	H	16370	18400	21180	24130
400	47.5	3	ts	H	10280	12000	14050	17070
			ts	HL	21860	25100	28950	34650
			bd	H	15970	17850	20660	23750
			bd	HL	29820	33250	38400	43850

500	36	2	ts	H	9960	11060	12340	13800
			ts	HL	19060	21130	23540	26300
			bd	H	14220	16590	17210	19210
			bd	HL	26220	28890	31710	35310
500	36	3	ts	H	12840	14370	16440	18600
			ts	HL	20290	22870	26140	29600
			bd	H	18880	20970	23720	27080
			bd	HL	28480	31570	35820	40780
500	42	2	ts	H	12080	13550	15520	18080
			ts	HL	24230	27100	30920	35980
			bd	H	16970	18890	21260	24350
500	42	3	ts	H	11060	12540	14450	16770
			ts	HL	18280	20640	23750	27420
			bd	H	17960	20170	22950	26250
500	58	3	ts	H	9550	10710	12140	13910
			ts	HL	19120	21310	23990	27410
			bd	H	13550	14920	16470	18420
			bd	HL	25700	28350	31220	34900
500	58	4	ts	H	10910	12350	14300	16630
			ts	HL	21110	23690	27270	31400
			bd	H	17220	19100	21350	24200
			bd	HL	30000	33300	37000	41900
600	48	3	ts	H	13420	14940	16970	19590
			ts	HL	23920	26590	30270	34890
			bd	H	20680	23050	25950	29750
			bd	HL	34000	37800	42300	48400
600	49	3	ts	H	12060	13300	14850	16600
			ts	HL	21570	27600	26450	29600
			bd	H	18650	20500	22600	25400
600	66	4	ts	H	10810	12080	13610	15190
			ts	HL	23810	26510	29710	33190
			bd	H	16820	18460	20420	22860
			bd	HL	33950	37260	41120	45960
600	66	5	ts	H	11490	13120	14890	16840
			ts	HL	19310	21870	24690	28010
			bd	H	20000	22200	24850	28250
			bd	HL	30200	33400	37350	42400
700	56	3	ts	H	11760	13100	14640	16840
			ts	HL	26600	29700	33140	38140
			bd	H	18670	20680	23100	26320
			bd	HL	38670	42830	47850	53820

[illegible]

700	56	4	ts ts bd	H HL H	12560 23680 21620	14060 26560 24100	16350 30900 27260	18540 34740 31200
700	56	4	ts ts bd	H HL H	11180 20740 19100	12280 22680 21030	23670 25170 23200	16240 30140 26000
700	78	5	ts ts bd bd	H HL H HL	8960 23330 15460 34440	10070 26150 17150 38200	11370 29270 19210 ——	13120 33750 22050 ——
700	78	6	ts ts bd bd	H HL H HL	10440 20890 20180 33300	11770 23420 22600 37200	13390 26460 25550 ——	15720 31070 29450 ——

3. Tabulation of the allowable compressive stress as determined from the interaction formula. All stresses and section characteristics are based on $t_w = 0.10$ and the use of triangular load distribution. The order of listing corresponds to the order used in the two previous parts. The moments of inertia were obtained from data made available by the Department of Naval Architecture at Massachusetts Institute of Technology.

n	I(in.^{4})	ℓ/r	P/A (psi)	M/Z (psi)	Allowable σ_p(psi)
1	31	48	1500	24400	15000
1	144	44.4	1150	20400	4700
2	620	37	1540	20500	6400
3	230	42	2440	22700	15200
3	440	37	2470	27000	
3	1070	38	2040	29600	
4	460	36	2800	27500	

[illegible]

[illegible]

[illegible]

1	60	56.5	1780	23200	12700
2	115	41	2780	24400	27000
2	394	40	2320	27100	
3	195	33.3	3350	19700	12400
3	675	33.8	2350	23300	17100
4	725	32.8	2570	22100	14300
2	74	46	6220	24400	62440
3	96	44.6	5250	22400	30900
3	550	38	3290	19500	12000
4	200	37.7	4970	21300	23500
4	620	37	3610	24800	44000
5	330	30	4890	17800	14400
5	990	34	3970	23300	29000
6	430	32	5260	20500	21900

APPENDIX F - BIBLIOGRAPHY

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